Thermal Drying of Wet Fuels: Opportunities and Technology

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REPORT SUMMARY

Renewable and alternative fuels often have moisture contents ranging from 40-60%. New drying technologies—especially those based on steam drying—make it possible to improve the thermal performance and economy of power plants fired with biomass or other high-moisture-content fuels. This report discusses the availability and properties of high-moisture fuels and describes different drying technologies and their applications.

Background

Evaporation of the moisture fed into the furnace as part of a high-moisture-content fuel consumes a minor but significant part of the energy inherent in the fuel. Furthermore, high fuel moisture content decreases combustion efficiency and increases the amount of flue gas passing through the boiler. While fuel drying has rarely been used in U.S. power plants, the process can make an important difference in the efficiency and cost of a power plant fired with renewable and alternative fuels. In particular, drying can benefit plants fired by wastes from the pulp and paper mill industry. EPRI and Imatran Voima Oy cosponsored this project to further investigate wet fuels and drying applications.

Objectives

To review the potential supply and characteristics of key high-moisture fuels and certain waste sludges formed by major industrial processes; to assess the applicability of available drying technologies for improving the attractiveness of these wet materials as alterative fuels; to conduct a preliminary assessment of three cases—wood cofiring, a wood-fired independent power producer, and retrofit of a fluidized bed.

Approach

Investigators first surveyed potential sources and characteristics of wet fuels and assessed the benefits of drying, as indicated through an evaluation of drying technologies. For the technology assessments they relied primarily on technical reports and other literature on fuels and drying technologies, supplemented with personal contacts. They next prepared cost estimates using vendor and other literature sources as well as in-house information. The cost estimates allow very preliminary comparison of dryer options. Finally, they examined three case studies in terms of integrating dryers into thermal power plants.

Results

With the high cost of landfilling and the increase in sludge generation due to the use of recycled fiber, pulp and paper mill sludges have become the largest potential source of fuels requiring drying. Evaluations of wood mill and logging residues, peat resources, and lignite showed them to be unattractive fuel options.

Fuel dryers are classified as either flue gas dryers or steam dryers. Flue gas dryers have historically been the primary type of dryers used for fuel drying, but during the last decade most of the R&D has focused on steam drying. Steam drying offers some clear benefits over flue gas drying: the possibility of recovering the energy used for drying, the lack of odor emissions due to closed cycle, and an inert steam atmosphere that eliminates the risk of fire. However, the investment cost for a steam dryer is usually higher than for flue gas dryers.

The drying of high-moisture-content fuel before combustion improves combustion and energy recovery, leads to a more flexible and stable boiler operation, and reduces the use of support fuel. It is also possible to increase the steam generation of an existing boiler or to build a new boiler of smaller size. Finally, fuel drying can substantially enhance the thermal efficiency of a plant firing wet fuel.

EPRI Perspective

“Green”electricity produced from renewable fuels is becoming more important. The inventory of wet fuels in North America is substantial, and the key fuel drying technologies can be applied in a wide variety of situations. One difficulty in the use renewable fuels with a high moisture content is that they must compete with the rather inexpensive fossil fuels. While drying is necessary to make these fuels a viable alternative, the fuel drying process may consume 10-20% of the available energy. Drying is therefore by far the most important step in energy efficiency improvement. This report will help utilities understand the differences between drying technologies in terms of commercialization, adaptability, capabilities, performance, and projected costs. Further studies are needed to evaluate the application of high-moisture-content fuels to advanced power plant concepts and to assess special drying integrations in the pulp and paper industry. EPRI report TR-105356 investigates the application of IVO's steam dryer to biomass gasification.

TR-107109

Interest Categories

Process industries
Biomass

Key Words

Biomass fuels
Resource assessment
Fuel drying
Alternative fuels
Thermal efficiency
Technology assessment

ABSTRACT

The Electric Power Research Institute funded the assessment of different fuel drying technologies and their potential integration in power generation systems using a variety of high moisture content fuels. Drying is of interest to electric utility operations which face continuing environmental pressures to utilize renewable fuels, many of which are wet, to displace fossil fuels.

The quantities and characteristics of high moisture content fuels in North America considered most likely to benefit from drying are pulp and paper mill sludges, mill and logging residues, peat, lignite and bagasse. The basic benefits of drying are identified including higher combustion temperature and boiler efficiency, more flexible boiler operation, less or no support fuel, boiler debottlenecking and potential operating disadvantages are described such as furnace ash slagging.

Flue gas dryers, the most common way of fuel drying today, are described. These include rotary, cascade and flash types. Steam drying is new and has been the focus of research and development during the last decade. Steam drying is accomplished in a nearly pure steam atmosphere. Benefits include improved thermal efficiency and reduced risk of fire and release of volatile organic compounds associated with flue gas dryers. The best opportunities for justifying dryers economically are identified as well as are the factors mitigating against dryer justification. Results of prefeasibility evaluations of hypothetical dryer applications are presented for wood co-firing in a large electrical utility generating station, a 12MW wood fired independent power producer, and retrofit of a fluidized bed furnace.

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SUMMARY

The purpose of this report is to give the reader a good understanding of the benefits of thermal drying of wet fuels, characterise the fuels that appear to represent the best opportunities and assess their availability, describe the technologies available and provide very preliminary analyses of several dryer applications.

Evaporation of the moisture accompanying wet fuel into a furnace consumes a significant proportion of the energy content of the fuel. Thus, fuel drying can make an important difference in the energy balance and economics of a power plant. Biomass and some other alternate fuels usually have a high initial moisture content. Now, utility operations face increasing competition, continuing environmental concerns, and pressures to utilize high moisture content fuels in a more efficient way to displace fossil fuels. Therefore, thermal drying may be a route to improved performance, economics and acceptability of existing utility power plants.

The Electric Power Research Institute retained H. A. Simons Ltd. to conduct an assessment of different fuel drying technologies and their use in power production from high moisture content fuels. The study includes: an inventory of high moisture content fuels in North America considered most likely to benefit from drying (pulp and paper mill sludges, mill and logging residues, bagasse and peat and lignite); an assessment of the benefits of drying and different drying technologies; and a review of capital, operating costs and environmental emissions of different drying processes; and dryer applications to Rankine Cycle power generation and cogeneration plants.

There are indications that in the future there will be a need for most of the electric utilities in North America to generate a portion of their output from renewable sources, of which biomass is a key component. Accordingly, EPRI members will be interested in understanding the differences between available drying technologies in terms of the level of commercialization, adaptability and capabilities, performance and projected costs of deployment.

INVENTORY AND PROPERTIES OF WET FUELS

- The wet fuels considered were those that are available in large quantities and which appear most likely to benefit from drying prior to combustion, namely:

- Pulp and paper mill sludges;
- Bark and other wood residues, left over from logging operations and from the wood processing but excluding roundwood or whole tree chips harvested specifically for fuel;
- Bagasse, from sugar cane processing;
- Peat and lignite.

The foregoing materials are renewable and continuously produced as industrial byproducts, with the exceptions of peat and lignite. These last two can only be considered to be renewable over a very long-term time frame. Nevertheless, peat and lignite are of interest as fuels now in utility use that can benefit from drying and be a bridge to utility use of renewable biomass fuels.

Properties

Moisture, ash, and carbon content are the main primary parameters that determine the heat content of the fuel. These and other physical and thermochemical characteristics of most interest for fuel properties and handling are presented in Table S -1.

Table S-1
Typical Physical and Thermochemical Properties of Selected Wet Fuels

			Pulp and Paper Sludge	Wood Residues		Milled Peat	Lignite	Sugarcane Bagasse
				Bark (c)	Fuel Chips			
Moisture Content		% Wet basis	50 - 65	30 - 60	45 - 55	45 - 55	30 - 50	48 - 52
HHV, dry basis	(b)	GJ/ODt	15 - 19	19 - 25	19 - 21	19 - 21	16.6 - 24.3	18.6 - 20.3
HHV, wet basis	(b)	GJ/ODt, MC	6 @35%	11 @ 50%	10 @ 50%	10@ 50%	12 @ 40%	10@ 50%
Bulk Density (wet basis)	(a)	kg/m3	500 - 900	290 - 380	260 - 320	300 - 400	650 - 780	80 - 130
Volatiles		% dry weight	-	69 - 76	70 - 85	60 - 70	50 - 60	84
<u>Ultimate Analysis</u>				Pine Bark	Douglas Fir			
Carbon		% dry weight	25 - 50	55.0	50.6	50 - 60	41.5 - 61.4	43.2 - 49.0
Hydrogen		% dry weight	3 - 6	5.8	6.2	5.0 - 6.5	3.4 - 4.6	5.9 - 6.6
Oxygen		% dry weight	19 - 38	39.0	43.0	30 - 40	11.3 - 19.7	43.4 - 48.0
Nitrogen		% dry weight	2 - 5	0.1	0.1	1.0 - 2.5	0.7 - 1.1	0.1 - 0.41
Sulfur		% dry weight	2 - 48	0.1	0.02	0.1 - 0.2	1.0 - 2.4	trace
Ash		% dry weight	3 - 50	3.0	0.1	2 - 10	11.9 - 40.6	1.4 - 2.9

NOTES:

a - Loose gravity packed material at typical moisture contents as compared with true or solid density.
b - ODt means Oven Dry tonnes or Oven Dry metric tons. For this and other abbreviations, refer to the Glossary in Appendix A.
c - bark which has been sized reduced, or hogged.

The moisture content of wood residues varies enormously, with wet wood bark from the north west coast with its high rainfall in winter as high as 65 - 70%, green wood and bark in the 50% range and residues from planer operations of kiln dried wood at 8 - 19%.

The higher heating value (HHV) of all of the selected fuels is, on a dry basis, remarkably closely grouped about 20 MJ/kg, a result of grouping of carbon content around 30 - 50% and hydrogen around 4 - 6%. If the comparison of HHV is made on an ash-free dry basis, the grouping is closer still, since ash represents a thermal dead load.

Compared with most conventional fuels excluding natural gas (usually desulphurized before distribution) , the selected wet fuels are low in sulphur even including most pulp mill sludges. Also, the nitrogen content is relatively low, except for pulp and paper mill sludges and peat, which contributes to low generation of NO_x emissions in combustion, since the nitrogen content of fuel has a great effect on NOx emissions.

Quantities

Pulp and Paper Mill Sludge The 5.6 million tonnes of pulp and paper sludge produced annually in North America is much smaller than that of other wet fuels considered. Today about 50 Oven Dry kg (OD) of sludge solids are generated on average per tonne of mill production, although this average value of 5% can be misleading as it varies so widely depending on the pulp and paper making process. However, the rapid increase in the use of recycled fibre, which can produce a high proportion of sludge per tonne of paper recycled - to 25% and more - has resulted in a high growth rates in sludge generation. The characteristics of these sludges are such that they have fewer alternative uses and are more difficult to dispose of in an environmentally acceptable manner.

To date, landfilling has been the predominant method of sludge disposal in North America. In 1989, 70 % of the sludge in the United States was landfilled, down from 86% in 1979. Burning increased from 11% to 21% over the same period. In US the average total cost of landfill sludge disposal amounted to $6.40 per cubic yard in 1989, and ranged from $1 to $25 to cubic yard. In an integrated mill situation, dewatered sludge is often added as a slip stream to the bark being fired in a grate type bark boiler, provided it represents a small proportion of the total grate fuel.

Landfilling is becoming increasingly costly and regulatory approvals more difficult to obtain. The recycling of the nutrient content of sludges back to land provides a holistic approach that may be applicable to many sludges. However, restrictions on the land application of some sludges due to the seasonality of land application programs, sludge composition (concern over the fate of heavy metals and dioxins), cost, and other factors, will favour burning for recovery of energy and volume reduction for ultimate disposal. The high moisture content of sludges makes them good candidates for drying, although North American pulp and paper mills are increasingly adopting fluidized bed boilers which are better able to burn sludges, and wet wood residues without significant support fuel unlike the grate type boilers commonly used.

With recycled fibre accounting for an increasing share of the pulp and paper industry output, sludge production is likely to grow much more rapidly than total industry output years ahead, presenting a growing sludge disposal problem.

Mill Residues In 1991 in US about 100 million ODt of mill residues were produced, of which only 5 % was unutilized. There is a higher proportion of unutilized residues in Canada, though in recent years use as fibre and as fuel has greatly increased.

At 40% of production, the largest single end-use was for use as fuel, followed closely by fibre products comprising fibreboard and sawdust-based kraft pulp. Total timber harvest in the United States could be increased by 40% by the year 2040, but with improving lumber recovery factors - more board feet per volume of log - the amount of mill residues generated will increase at a lower rate.

Rising fibre prices make it increasingly uneconomic to utilize the wood component of mill residues as fuel. Some drying of mill residues used as fuel has been done in the past, but fluidized bed boilers are becoming more and more popular in the forest sector, as they can handle sludge as well as wet bark. Some niche market opportunities for drying mill residues may exist where an existing boiler has to deal with an increasingly wet fuel mix.

Logging Residues It is estimated that up to 130 million OD tonnes of logging residues are produced in North America annually, but the cost of recovering much of this material is very high. As a result, it is considered likely that this material will be primarily used as fibre, when it is utilized during high points in the fibre market cycle, with a small portion of byproduct bark and off-specification chips available as fuel. More dispersed, smaller residues, consisting of branches and foliage, are most expensive to harvest and will likely be left on site in any event for environmental reasons, including nutrient recycling. In any event, the moisture content of logging residues though variable is typically 50% or less, making it a lower priority candidate for drying than other wet fuels being considered.

Peat While North America has enormous peat resources, it is unlikely that those will be utilized for energy production in the foreseeable future, given the cost and environmental constraints associated with peat harvesting. As no reversal of this trend is foreseen in the near future, peat is considered to be an unlikely target market for new drying technologies in North America.

Lignite More than 90 million tonnes of lignite were mined in North America during 1995, primarily for use in mine-mouth power plants. The moisture content of lignite often reaches 40% in North Dakota lignites, but to date most power plants have not found it economic to dry lignite.

Bagasse Only about 3.4 million tonnes of bagasse are produced annually in the United States, most of which is utilized as fuel in sugar plants. While bagasse is sometimes dried before use as fuel, it more often is burned at the 50% moisture content level at which it is produced. A number of flue gas dryers are known to be installed in Hawaii.

The quantities of the selected wet fuels in North America are summarized in Table S - 2.

Table S - 2
Summary of North American Quantities of Wet Fuel with Potential for Drying

	Annual Production, million ODt			Resources, million ODt			HHV Dry Basis	Supply Cost
	U.S.	Canada	Total	U.S.	Canada	Total	GJ/ODt	$/ODt
Pulp and Paper Sludges	4.2	1.4	5.6				15 - 19	(70) (d)
Mill Residues	100.5	18.4	118.9				19 - 25	0 - 20
Logging Residues	109.5	21.4	130.9				19 - 21	30+
Peat	0.6	1.1	1.7	71,000	335,000	406,000	19 - 21	40
Lignite	79.9	10.7	90.6	33,600	2,200	35,800	17 - 24	8 - 13
Bagasse	3.4	0	3.4				18 - 20	0

NOTES:

a) Quantities from tables in foregoing section.
b) Lignite resources are restricted to "recoverable reserves", as defined in text.
c) U.S. logging residue production estimates ranges from 39.1 to 109.5 million ODt/year
d) Negative supply cost, disposal cost taken as 10$US/cu. yard (approx. 13$/m3= 13.3 $US/wet tonne) and 185 ODkg/m3

BENEFITS OF DRYING

Drying whether it occurs in the furnace or before firing is an important part of the conversion process from fuel to the useful end products of power and heat. Typically the moisture content of the wet biomass fuels and different dewatered sludges is in the range of 40-60% which means that roughly 10-20% of the energy available in the dry fuel has to be used for evaporation of the moisture. Dry fuel burns more readily and vigorously than wet fuel which results in higher combustion efficiency and need for less excess air.

Key combustion parameters are improved by drying: the adiabatic flame temperature, the boiler efficiency and the steam generation are raised, and the volume of flue gas is reduced. These contribute to:

- More flexible and stable boiler operation, using less or no support fuel

- Increased thermal output or steam generation for an existing boiler (debottlenecking)
- Smaller size and cost for a new boiler of same thermal output
- Reduced fan power
- Improved thermal efficiency
- Lower furnace emissions of particulate matter and volatile organic compounds, higher nitrogen oxides
- reduced gas velocities and potential for erosion of boiler tubes

For grate-fired boilers, the adiabatic combustion temperature must be maintained above 1100 - 1400°C for adequate control and burnout of fuel particles. In some cases additional fossil fuel has to be burned with high moisture content fuels, a practice which can be avoided by drying the fuel. Fluidized bed boilers operate with a lower adiabatic combustion temperature which can be as low as 1050 - 1100°C and are consequently more easily operated without support fuel with high or varying fuel moisture content. In the case of fuel that is too dry, bed temperature control may require recirculation of flue gases. In a pulverized fuel fired boiler, the fuel has to be of fine particle size, and is usually dried before or during pulverising.

Reduced moisture in the fuel reduces the volume flow rate of the flue gases, the overall boiler dimensions including the grate, fan sizes in a new boiler significantly reducing costs for a given steam generation or heat output. In an existing boiler the steam generating capability of the boiler can usually be increased because of reduced carryover (particulate loading leaving the boiler), erosion of boiler tube banks and induced draft fan capacity requirements.

The drawback to fuel drying is that the dryer is additional cost and complexity, the latter affecting overall system availability. In addition, ash fouling and slagging tendency increases. Fouling or slagging which is the build up of furnace deposits leads to poor heat transfer, more fan power, more sootblowing and eventually downtime to unplug flue gas passages and remove deposits on furnace surfaces. Such deposits drastically decrease availability due to the need to take downtime for their removal. The worst problems of slagging are associated with elevated alkali metal content, principally sodium and potassium, both common in biomass fuels, high ratio of alkaline metal oxides to silica, and by the presence of sulphur. Sulphur is normally low in biomass fuels, but common in fossil fuels. The susceptibility of wet fuels to slagging problems can be estimated from fuel ash chemistry and furnace temperature profile.

The justification for drying depends on the price of wet and support fuel, cost or value of electricity, the investment costs, the type of fuel dryer that is being considered, and, in the case of retrofit applications, the specifics of the existing boiler plant. In the latter case, retrofitting a dryer may offer benefits that are not available with a new facility, due to the potential which may exist for debottlenecking.

With grate firing, the particulate matter (PM) will be reduced after fuel drying in most cases because of improved combustion, except where fine material comprises a high proportion of the wet fuel. For fluid bed furnaces and for pulverised fuel suspension firing, PM emissions leaving the boiler are expected to be insensitive to fuel moisture level.

With drier fuel, the higher furnace temperatures will tend to increase the formation of nitrogen oxides, though modern overfire air systems show markedly reduced NO_x formation than older designs. When NO_x emissions from the firing of biomass fuel, even after drying, are compared with natural gas fired in conventional burners they are at similar levels, while when compared with oil and coal are significantly lower. However, low NO_x burners are an active area of development and some natural gas and oil burners are capable of very low emissions, significantly lower than that from a conventionally designed biomass boiler.

The origin of the volatile organic compound emissions from boilers are a small fraction of the pyrolysis gases that evolve during combustion process of the wood or other fuel, but are not oxidized before leaving the furnace. Any such emissions would decrease with the better combustion associated with drier fuel.

FUEL DRYING TECHNOLOGIES

Fuel drying technologies can be divided into two groups depending on the drying medium: flue gas drying and steam drying.

Flue gas drying

Flue gas dryers are well established technology and still today the most common way of fuel drying. However, there has been a significant drop in flue gas dryer sales in the last decade reflecting lower fossil fuel prices.

In a flue gas dryer the energy for drying is supplied directly by the flue gases leaving the boiler. The gases are further cooled as a result. The dry fuel is then separated from the flue gas usually by a cyclone collector, and the flue gas along with the evaporated moisture is ducted to the emission control equipment and the stack. The partial pressure of the water vapor in the flue gases is usually so low that the utilization of the latent heat of the water vapor is not possible without a heat pump, and thus the latent heat of vaporization is generally lost. Of course, this heat is also lost when no drying is done. The use of a flue gas dryer generally may mean that combustion air preheating is more economically achieved using extraction steam from the steam turbine since the temperature differences available in the flue gas leaving the dryer are too low for a cost effective air heater.

The disadvantages of the flue gas dryer are the risk of fire due to the high temperature and the oxygen content of the gas, which is normally in the range of 4 - 8% by volume. A further disadvantage is the release of volatile organic compound emissions some of which are odorous and caused by the organic compounds released during drying. Increased flue gas temperature increases the organics release and is normally limited to about 320°C, though flash drying temperatures can reach 430°C. The compounds may also cause tar-like deposits on the surfaces at low temperature in the flue gas ducts.

The most important types of flue gas dryers in use are rotary dryer, flash dryer and cascade dryer.

The rotary dryer is a horizontal, slightly inclined rotating drum through which flue gases are passed. The fuel is conveyed by the rotating movement of the drum. The fuel residence time in the rotary dryer is 20 - 30 minutes or relatively long which allows large particles to dry properly. Manufacturers of rotary dryers are quite numerous including M-E-C Inc, Rader Inc, Raytheon, and ABB Raymond.

The cascade dryer is a short vertical vessel with conical bottom and top with flue gas entering the bottom and leaving at the top. The wet fuel is introduced along with the flue gas. The cascade dryer is manufactured by ESI Inc. in North America and ABB elsewhere.

In a flash dryer the particles are conveyed by the flue gas which requires the particle size be small. This is achieved by pulverizing, hogging or milling before drying. Flash dryers are manufactured by ABB Raymond, Ahlstrom of Finland, and William Patent Crusher and Pulverizer Co., Inc. of the US.

Further comparative technical information is summarized in Table S - 3 that follows.

Steam drying

The research and development of fuel drying technologies has during the last decade mainly concentrated on different steam drying technologies. Currently, there are two to three steam dryers commercially available, and a like number at the advanced development stage.

Steam drying is accomplished in a nearly pure steam atmosphere. The virtual absence of flue gas, air, or other non condensible gases means that all the condensation can potentially occur at a single temperature governed by the dryer pressure. This allows recovery at a high temperature of the latent heat of vaporization of the fuel moisture evaporated which makes it most useful for process heating. This aspect of steam drying contrasts with flue gas or other types of dryers, where the non-condensible gases and water vapor condense at lower temperatures making the heat recovered less useful for process heating..

Hence steam dryers are best suited for industrial or back pressure power plants where there is use for low pressure process steam, or hot water. In principle, it is also possible to raise new steam in a reboiler that can be fed back to the condensing section of a steam or organic Rankine turbine for power generation, or compress the steam to a higher pressure so that the steam can be reused at a higher temperature.

The other advantages of steam drying are that steam is an inert atmosphere, and so the risk of fire is absent. A drawback is the steam produced in the dryer contains organic compounds which make some type of treatment mandatory for the contaminated condensate. The condensate has a high biochemical oxygen demand and is corrosive.

This study has identified myriad different approaches to steam drying. Steam drying technologies may be atmospheric or pressurized, have short to long residence time, be large or small, and take very different forms physically. Also, heat sources may be hot combustion gases, high pressure steam, hot bed material from a fluid bed furnace or by means of a steam compressor type heat pump. The main differences among types are in the way the heat is provided to the dryer and in the operating pressure and temperature.

The manufacturers of steam dryers include Stork Friesland Scandinavia of Sweden, Niro Atomizer of Denmark, Lurgi of Germany, and IVO of Finland

The Stork Friesland uses co-axial tubes with heat supplied typically by the condensation in the outer tube of steam extracted from a steam turbine generator. The drying is accomplished by pneumatically conveying the wet material within the inner tube. Stork have commercialized their dryer and more installations than other suppliers.

Niro Atomizer of Denmark has developed and commercialized their Superheated Steam Fluid Bed Dryers for the drying of Sludges and other materials in the agricultural industry as a part of byproduct reprocessing. Niro have at least 10 installations.

Lurgi of Germany uses a fluidized bed consisting of the material being dried itself, with fluidizing provided by recirculating steam. Heating of the wet material and reheating the superheated steam is by a heat exchanger tube bundle which is immersed in the bed material and provides very high rates of heat transfer. The heat source would normally be fresh high pressure steam. Proposed applications include: peat, lignite, sewage sludge, pulp and paper mill sludge, agricultural byproducts, ore and mineral sediments.

All of the above steam dryers can use either external sources of heat, or, alternatively, mechanical vapor recompression, which decreases the external energy needed for drying considerably.

IVO of Finland has developed a high pressure flash dryer where heat is provided by external heat exchanger that can be located after the generating bank in the flue gas back passes of a boiler. With this application the temperature levels are relatively high so that the evaporated moisture can be more usefully utilized elsewhere in the process. IVO has also a prototype demonstration fuel dryer, the Bed Mixing Dryer, which uses hot bed material withdrawn from a fluidized bed furnace as the heat source for drying. The dryer operates at furnace pressure, close to atmospheric pressure, so that the evaporated moisture can only be utilized in the process at relatively low temperature levels.

Further comparative technical information is summarized in Table S - 3 that follows.

Table S-3
Thermal Dryers: Representative Comparative Characteristics by Type

Type or Company	Name of System	Evaporative Capacity Range, t/h	Operating Temperature in Dryer, °C	Average Residence Time, Order of Magnitude, s	Number of Installations Identified
FLUE GAS DRYERS					
Rotary-type	-	3 - 23	120 - 320	1000 - 2000	>1000
Cascade-type	-	2 - 41	120 - 320	120	~ 30
Flash-type	-	5 - 17	200 - 430	2 - 10	~ 14
STEAM DRYERS					
IVO	High Pressure Steam Dryer	(a)	130 - 205	2 - 3	(a)
IVO	Bed Mixing Dryer	(b)	~ 100	-	(b)
Lurgi	SFBD, Steam Fluidised Bed Dryer	>150	120 - 150	-	©
Niro	Superheated Steam Fluid Bed Dryer	1 - 40	150 - 170	300	~ 10
Stork	Exergy Steam Dryer	0.3 - 63	130 - 180	10 - 100	~ 15

NOTES:
a - One 0.7 t/h pilot plant
b - One demonstration plant of 5.6 t/h
c - several developmental prototypes.

Capital cost information was obtained from the technical literature and from several manufacturers, but was not a priority for this survey-type study. The technical literature included several dryer-specific studies undertaken in the early 1980s covering mainly flue gas dryers. This information was brought to today's prices using escalation factors, and is presented in graph form in Figure 4 - 3. This information was supplemented with budgetary information from several vendors of steam dryers. Based on this information, order of magnitude capital costs for drying from 55 to 35% or lower moisture content, appear to be about 1.5 - 3.5MUS$ for 4 oven dry tonnes/h, 2 - 5MUS$ for 10 oven dry tonnes/h, and 6 - 12MUS$ for 30 oven dry tonnes/h for both flue gas and steam dryers.

Environmental Aspects

During drying of wet fuels, not only is water evaporated and particulate mater entrained by the flue gas, but also many different kinds of organic compound groups are volatilized as well. Some of these contaminants are removed in part by the emission control system before release to the atmosphere, others will pass through undiminished to the stack and atmosphere. The amount of particulate matter in the flue gas leaving a dryer is likely lower than that in the flue gas entering, resulting in reduced stack emissions. Some such reductions are reported to be as high as 50 - 80%. The mechanism for such reductions is by impaction of finer material on coarse wet fuel particles, but it is clear that reduction is not always the case, particularly if the wet fuel is composed principally of fine material and the stack emission limit is stringent.

Though both flue gas and steam drying processes use relatively low temperatures of 100 - 400°C, the thermal treatment brings about changes in the organic material, even under the more mild of these conditions. As they contain a larger proportion of volatiles, the release of these components is greater for wood, bark and wood-derived residues than for than peat, lignite or bagasse. The organic compounds released may also cause operational problems downstream by contributing to the formation of tar-like deposits if conditions favor condensation on duct and other surfaces. In the case of wood and wood residue drying, the groups of compounds of most significance to air emissions are the volatile monoterpenes, other condensable lipid compounds and products of thermal degradation. The products of thermal degradation of wood include acetic and formic acids, alcohols, aldehydes, furfurals, and carbon dioxide. These are released starting at 100°C and above, but become significant at higher drying temperatures, particularly above 200°C. Some degree of control of volatile organic compound emissions in the process from flue gas drying is achieved by lowering peak temperatures, recycling of part of the flue gas leaving the dryer back to the inlet, and reducing the quantity of fine material in the dryer feed material and its residence time.

INTEGRATION OPPORTUNITIES

Types of Systems with Potential for Drying

Factors that appear to provide the best opportunities for justifying dryers economically are when:

- Expensive fuels are displaced : The substitution of an expensive with less expensive biomass fuel is more easily justified the wider the price spread. The higher the cost of a wet biomass fuel, the more easily the additional expense and complexity of a dryer system can be justified;
- Fossil fuel is used to improve boiler flexibility and control: If the use of fossil fuel is needed to sustain combustion of wet fuel on the grate, then external drying of the wet fuel may be sufficient to reduce or eliminate the need for sustaining fuel;
- Existing Boiler and ancillary equipment limit the amount of wet fuel that can be fired: If the boiler requires supplementary firing to meet steam demand, or the boiler tube erosion rates or fan capacities are the limitations to burning more wet fuel on the grate, then drying of wet fuel will be advantageous;
- Elevated stack emissions present an air emission permitting problem If the particulate, volatile organic compound or other emissions are the limitations to burning more wet fuel, often the case with grate-type boilers, then the use of a dryer , by improving combustion will be advantageous.
- Low temperature heat is needed in the steam cycle A steam cycle which permits the recovery of the latent heat in the moisture evaporated from the fuel will result in improved overall system thermal efficiency. This gain will be in addition to the improved combustion efficiency. In this case, a steam dryer which improves both the combustion efficiency and the steam cycle efficiency may be more easily justified economically than a flue gas dryer.

Similarly, other factors appear to mitigate against the economic justification of dryers:

- Wet fuel is more than 52 - 55% moisture wet basis, where mechanical pressing generally proves to be more cost effective than thermal drying. However, this does not mean that drying to lower levels than this level would not be justified on its own merits.
- Biomass or sludge fuel that is free or of negative cost. The substitution of fossil fuel by a low cost renewable fuel is more easily justified the lower the cost. When the cost is negative, that is when a material has a disposal cost or tipping fee associated with it, the economics can improve dramatically. However, it is more difficult to justify fuel drying, the lower the cost of the renewable fuel in most cases, unless the boiler system is bottlenecked because of the moisture in the fuel;

- Retrofit situations where the stack temperature is already low; In the case of an existing wet fuel boiler where the stack temperature is already low and cannot be lowered further because of the risk of corrosion of emission control equipment, ducting and stack, the addition of a dryer would require a separate dried fuel burner for a heat source, further adding to the investment and complexity of the system and making justification less easy;
- Ash deposition or slagging problems Where the ash analysis indicates a high ratio of alkaline metal oxides to silica, the slagging and fouling tendencies of the boiler will be increased with the increased temperatures resulting from drying wet fuel.
- Absence of a biological treatment system; Flue gas dryer systems will be favored over steam dryers in the absence of a biological treatment system for treating the contaminated condensates from steam drying. If the plant uses wet scrubbers, whatever the drying system, treatment will be required of the scrubber effluents. The installation of a dedicated stand alone treatment system adds to the complexity and cost particularly if toxicity is to be removed.

Cases Considered

Preliminary evaluations of dryer applications to three types of boilers all of which involve power generation were undertaken. The cases analyzed were:

- the hypothetical retrofit of 10% wood cofiring to large 300MW electrical utility generating station assuming different base design fuels fired of 100% gas, 100% heavy oil and 100% coal;
- a small existing 12MW wood residue only fired independent power producer, where power output was limited by a boiler bottleneck;
- retrofit of a fluidized bed furnace to a large existing wood residue fired boiler in a large kraft pulp mill where power is to be generated with a new condensing steam turbine.

For each case, preliminary heat balances were prepared and the economics have been based on order of magnitude or factored estimates suitable for preliminary screening or comparative feasibility purposes. Simple paybacks were in the range of 4.4 to 25 and more years depending on the application cases, the drying technology and fuel costs assumed.

1

INTRODUCTION

Background

The potential of drying technologies in the generation of power and heat is evident given the increasing interest internationally particularly at the policy level in alternative fuels. These include wood waste, peat, lignite, some carbon rich industrial and agricultural by products or waste streams which contain significant moisture such as pulp and paper mill sludges.

This study has been undertaken to assess available drying technologies, the process approach used, capabilities and performance, suitability for the feedstocks that would most benefit from drying, thermal efficiency, capital and operating costs, level of commercialization, and discernable trends. Recognizing that much technological survey work of this type was done in the early 1980s and is still relevant, the focus has been on changes in approach, new commercialized technologies and new areas of application to supplement the findings of these earlier studies.

In January 1996, the Electric Power Research Institute (EPRI) awarded the assignment to H. A. SIMONS Ltd. EPRI is funded by 700 utility companies in the USA with participation of utility companies of several other countries through associate membership. Its research work focuses on generation technology, transmission and electricity use, cost effectiveness and environmental concerns.

There are signs that in the future there will be a need for most of the electric utilities in North America to generate a portion of their output from renewable sources, of which biomass is a key component. This will allow the utilities to work towards CO_2 abatement. Accordingly, EPRI members will be interested in understanding the differences between available drying technologies in terms of the level of commercialization, adaptability and capabilities, performance and projected costs of deployment.

Purpose

To review the availability, chemical and physical characteristics of the key high moisture fuels and certain waste sludges formed by major industrial processes, to assess the applicability of available drying technologies to improve the attractiveness of these materials as alternative fuels, and to conduct a prefeasibility evaluation of several cases.

Approach, Assumptions and Limitations

The report consists of two parts: a survey in Section 2 presenting sources and characteristics of wet fuels and technical sections, Sections 3 - 5, comprising descriptions of the benefits of drying, drying technologies, and case studies of integrating dryers into thermal power plants.

The study relies firstly on technical reports and literature of the survey type to the maximum extent possible. Where necessary, the information has been supplemented with a limited number of personal contacts to ensure at least some coverage for all parts of the study mandate within the budget envelope. The data is presented in summary form and for confirmation and more detail and in the case of equipment performance, the reader is advised to refer to the original source literature. A reasonable level of knowledge by the reader is assumed. All sources of information used are listed by author name in the References presented in Appendix B.

Estimate of cost information has been prepared using supplier and literature sources supplemented by some in-house information where appropriate data was available. The cost estimates are presented to allow very preliminary comparison of dryer options.

In the limited number of comparisons between in-house cost data and literature-based costs, the latter were shown in some cases to be low estimates by a wide margin. In any formal screening of technology alternatives, estimates based on preliminary engineering of the facility or system are required. This would comprise: preparation of technical specifications and comparisons of bid information supplied by equipment vendors; estimates of civil/structural, mechanical, electrical and process control systems; and indirect costs for such items as construction management, engineering, owners site costs and contractor’s overhead. Accordingly, there may be substantial differences between the costs presented here and the costs for a particular installation as estimated during definition engineering. However, the cost estimates presented in this report are illustrative of the order of magnitude of total installed costs that can be expected in the U.S. at the end of 1995 and are presented in U.S. dollars.

2

INVENTORY AND PROPERTIES OF WET FUELS

Background

This section presents an overview assessment of selected wet fuel quantities potentially available for use as fuel and their physical and chemical properties which are most relevant to combustion processes. The study terms of reference narrows the range of potential fuels to those considered to be the most promising in terms of benefitting from drying. Those selected in descending order of interest are:

- Pulp and paper mill sludges;
- Bark and other wood residues;
- Peat, lignite, and bagasse

The foregoing materials are renewable, continuously produced as industrial byproducts with two exceptions: peat and lignite. Peat and lignite resources are large stocks of material which can only be considered to be renewable over a very long-term geological time horizon. They have been included in this study since they are high moisture content fuels which could potentially benefit from the application of drying technologies.

The inventory assessment is restricted to wood residues, or waste left over from logging and the wood processing that occurs in pulp mill, sawmill and boardmill operations. Roundwood or whole-tree chips harvested specifically for fuel from either native or cultivated forests are excluded.

Brief mention is also made of municipal waste water treatment sludges, because of the large amount generated annually and to provide further perspective on wet fuel quantities.

Other potentially significant renewable fuels include non-recyclable paper, agricultural byproducts such as rice hulls, straw, all of which are excluded since they normally require no further drying for combustion processes.

The next subsection looks briefly at the properties of the selected fuels as a group. This is followed by subsections examining each wet fuel in terms of the following criteria:

- Quantities available
- Ease and cost of collection and disposal
- Seasonality
- Competition for the material
- Environmental issues associated with use
- Existing and potential incentives or disincentives for use
- Physical and chemical characteristics which might either constrain or foster use of wet renewable fuels.

The industrial processes generating these materials are not static as they continuously respond to technological, economic, environmental, and other inputs and constraints. This creates uncertainty in projecting supply availability and price, and tends to limit the utilization of these materials as fuel to levels which are far below their availability. For this same reason, the information on the quantities available and prices are approximate, order-of-magnitude estimates only, developed from the sources and direct contacts indicated. To respond to this uncertainty which affects candidate wet fuels for drying technologies, the examination of inventory quantities includes a discussion of key factors which are anticipated to affect the future availability of these materials.

Overview of Physical and Chemical Properties

Physical and thermochemical characteristics of the selected wet fuels which determine their usefulness as fuels is presented on a comparative basis in Table 2-1 that follows.

Moisture content, along with carbon and hydrogen content, are the three primary parameters determining the heat content of all biomass fuels. In this report, % moisture content is expressed on a wet basis, and is numerically equal to 100% less the % solids or the % dryness.

In the case of sludges, moisture content makes a significant difference in the fuel value and hence the ease of incineration. Very wet primary treatment sludge dewatered to 25% solids, or 75% moisture content, which is typical of old mills, would have a higher heating value of about 5100 kJ/wet kg. As such, the material is close to the point where it actually reduces steam generation because the heat absorbed to vaporize the water in the fuel and carried away by the flue gases absorbs almost all of the heat supplied in the dry fraction of the sludge. In many older boilers, burning sludge requires the firing of fossil fuel to maintain combustion stability even when the sludge represents a relatively small portion of the fuel fired.

By contrast, the drier sludge produced by modern sludge dewatering installations where solids and moisture content may be about 50%, the higher heating value increases to about 10 000 kJ/wet kg. At this dryness, sludge would make a contribution to steam generation, though the material is still too wet to be considered a highly desirable fuel from an operating point of view in older stoker fired equipment.

Higher heating value is presented for both oven dry material and for a typical level of moisture which is stated. Heat content on an oven dry basis indicates the potential or ultimate fuel value. It is noteworthy how closely the values are grouped around 20 000kJ/ODkg, with the exception of pulp and paper mill sludges which range lower due to their often higher inerts content. The typical higher heating value on a wet basis is presented to indicate the marked deterioration in fuel heat content that occurs due to moisture in the fuel.

Table 2-1
Typical Physical and Thermochemcial Properties of Selected Wet Fuels

			Pulp and Paper Sludge	Wood Residues		Milled Peat	Lignite	Sugarcane Bagasse
				Bark (c)	Fuel Chips			
Moisture Content		% Wet basis	50 - 65	30 - 60	45 - 55	45 - 55	30 - 50	48 - 52
HHV, dry basis	(b)	GJ/ODt	15 - 19	19 - 25	19 - 21	19 - 21	16.6 - 24.3	18.6 - 20.3
HHV, wet basis	(b)	GJ/ODt, MC	6 @35%	11 @ 50%	10 @ 50%	10@ 50%	12 @ 40%	10@ 50%
Bulk Density (wet basis)	(a)	kg/m3	500 - 900	290 - 380	260 - 320	300 - 400	650 - 780	80 - 130
Volatiles		% dry weight	-	69 - 76	70 - 85	60 - 70	50 - 60	84
Ultimate Analysis				Pine Bark	Douglas Fir			
Carbon		% dry weight	25 - 50	55.0	50.6	50 - 60	41.5 - 61.4	43.2 - 49.0
Hydrogen		% dry weight	3 - 6	5.8	6.2	5.0 - 6.5	3.4 - 4.6	5.9 - 6.6
Oxygen		% dry weight	19 - 38	39.0	43.0	30 - 40	11.3 - 19.7	43.4 - 48.0
Nitrogen		% dry weight	2 - 5	0.1	0.1	1.0 - 2.5	0.7 - 1.1	0.1 - 0.41
Sulfur		% dry weight	2 - 48	0.1	0.02	0.1 - 0.2	1.0 - 2.4	trace
Ash		% dry weight	3 - 50	3.0	0.1	2 - 10	11.9 - 40.6	1.4 - 2.9

SOURCES:
Sludge: H.A. Simons Ltd.
Wood Residues: Bulk densities from Nielson, 1985; moisture content and HHV from Appel, 1993. Ultimate analyses: pine bark from Hollenbacher, 1992; douglas fir from Jenkins, 1993.
Peat: Ultimate analysis and bulk density from Monenco Ontario Ltd., 1981; other properties from H.A. Simons, 1994(a).
Lignite: range of values based on design analysis for lignite from McLean County, North Dakota and Atacosa and McMullan Counties, Texas (Nowacki, 1980); bulk density from Monenco Ontario Ltd., 1981.
Bagasse: Singer, 1991.
NOTES:
a - Loose gravity packed material at typical moisture contents as compared with true or solid density.
b - ODt means Oven Dry tonnes or Oven Dry metric tons. For this and other abbreviations, refer to the Glossary in Appendix A.
c - bark which has been sized reduced, or hogged.

Volatile content determines the ease with which fuels burn, since it is these vapours initially released that first ignite and initiate combustion. However, low volatility does not necessarily make a poor fuel. For instance, coke is an excellent and very hot fuel, produced by the distillation of coal. However, with virtually no volatiles and containing high carbon content it is difficult to ignite and requires high ignition temperatures.

The ultimate analysis presents the chemical composition of the main constituent elements of the fuel. The inerts include those compounds that normally undergo little change during the combustion process and leave the combustion process as ash.

Pulp and Paper Mill Sludges

Types of Sludges Considered

The pulp and paper industry produces sludges and sludge-like materials in large quantities. The most plentiful are those containing fibre and of most interest here as they have potential as a fuel particularly when dried. Other sludge-like materials such as those from raw water treatment and green liquor dregs are mainly inorganic and of mineral origin. As they have no potential as fuels they are therefore excluded. For purposes of this study, the selected sludges are grouped into three categories: primary, secondary, and recycled paper sludges.

- Primary sludge, which is derived from the clarification of untreated mill effluent, is a mixture of organic and inorganic materials. The major component is wood fibre, while inorganic components include clay, calcium carbonate, titanium dioxide, and sand and grit, depending on the type of mill.
- Secondary sludge results from the sedimentation of biologically-treated mill effluent, and is principally composed of microbial biomass, and contains very little mineral matter.
- Recycled paper mill sludge, in the form of fibre containing fillers, ink and other contaminants, is derived from processing recycled fibre, is a special form of primary sludge. It is differentiated here from primary sludge because of the growing importance of recycled paper production, and the high proportion of sludge produced per unit of recycled pulp production which can range from 15 to 50% or more. Also sludges from recycled paper mills present a very wide range of percent inerts depending on the recycled material being processed, the finish product and the process being used. Most mills, however, have sludges with inerts in the 20 - 50% range.

Sludges result from the screening, flocculation or sedimentation of dilute suspensions of solid material in pulp and paper mill effluents. On settling, the solid material is initially at very low concentration. Through processes of thickening and dewatering, these materials are brought to the 15 - 50% solids content range, equivalent to 85 - 50% moisture wet basis. In older mills with the less effective vacuum filters, primary effluent treatment sludges are brought to the 15 - 25% solids before disposal or burning. More modern screw presses, even when including difficult-to-dewater secondary sludge, would typically be able to achieve 45 - 55% solids.

Quantities Available

Sludge Production in the United States

In total, about 4.2 million dry tonnes of pulp and paper sludges are estimated to have been generated in the U.S. in 1989, based on projecting the survey responses covering about two-thirds of the total output of paper, paperboard and market pulp (NCASI #641, 1992).

A survey of U.S. pulp and paper mills in December 1989 found that, for all types of mills, about 50 ODkg of sludge solids were generated on average per tonne of mill production. The survey results indicated that sludge generation rates are highly variable, not only between different types of mills, but even among mills with similar production processes (NCASI #641, 1992).

The variation in sludge generation rates per unit production among major product types, as reported in the NCASI survey, is illustrated in Table 2-2. Rates of primary sludge production from deinking plants is shown to be an order of magnitude higher than that of other types of pulp and paper mills. With recycled fibre accounting for an increasing share of the pulp and paper industry output, sludge production is likely to grow much more rapidly than total industry output in the years ahead, presenting a growing sludge disposal problem.

Table 2-2
Average U.S. Pulp and Paper Sludge Generation Rates by Production Category

Production Category	Primary Sludge OD kg/t	Secondary Sludge OD kg/t	Dredged Sludge OD kg/t
Bleached kraft	57	27	20
Unbleached kraft	24	8	8
Semi-chemical	19	19	4
Sulfite	54	28	13
Groundwood	71	18	5
Deinking	270	25	1
Recycled Paperboard	33	7	6
Non-integrated	33	7	6
Overall	60	21	12

Sludge Production in Canada

Sludge generation by pulp and paper mills in Canada totals about 1.4 million dry tonnes or about one third of that generated in the US. The sources have been estimated as follows (Caule, 1995):

Production ('000 t)	Dry solids
Primary sludge	691
Secondary sludge	260
Deinking sludge	400
Total	1,351

Alternative Disposal Options

Secondary sludges are difficult to dewater alone, so are often mixed with primary sludge before dewatering. Dewatering of the combined sludges is usually carried out in several stages. The use of belt presses, followed by high-intensity screw presses, has reported achieved consistencies of higher than 50% (Caule, 1995). Polymers may be added to assist the presses in producing higher levels of solids in sludges.

The results of a recent NCASI survey established the percentage of U.S. mills using each major dewatering method and are summarized in Table 2-3. The belt filter press is shown to be the most common method, with 45% of the reporting mills employing this option, followed by the screw press, at 17%. The percentage of mills using land-based dewatering/storage and vacuum filters for sludge dewatering has declined to about 12% for each method in recent years.

Table 2-3
Sludge Dewatering Methods Used by U.S. Pulp and Paper Industry, 1989

	Primary Sludge	**Secondary Sludge**	**Combined Sludge**	**Total**
Land-based dewatering (e.g.,	15%	28%	4%	12%
Belt filter press	36%	38%	59%	45%
Screw press	18%		20%	17%
Vacuum filter	15%		11%	12%
Filter press	1%		3%	2%
Centrifuge	1%	6%		1%
V-Press	6%		3%	4%
Other	8%	28%		7%
Totals	100%	100%	100%	100%

To date, landfilling has been the predominant method of sludge disposal in North America. Trends in U.S. pulp and paper sludge disposal options are indicated in Table 2-4. In 1989, 70% of the sludge was landfilled or lagooned, down from 86% in 1979. Burning increased from 11 to 21% over the same period, while land application grew from 2 to 8%.

Table 2-4
Disposal of Pulp and Paper Wastewater Treatment Sludges

Table 2-4
Disposal of Pulp and Paper Wastewater Treatment Sludges

	1979	1988/89
Landfill or lagoon	86%	70%
Burning for energy	11%	21%
Land Application	2%	8%
Recycle/reuse	<1%	1%
Other	<1%	<1%

Source of Tables 2-2 to 2-4: National Council of the Paper Industry for Air and Stream Improvement Inc. Technical Bulletin No. 641: Solid Waste management and Disposal Practices in the U.S. Paper Industry. Sept. 1992.

By comparison, about 47 % of primary and secondary sludge was burned in Canadian pulp and paper mills, according to a 1995 estimate (Caule, 1995), with the remainder landfilled. The larger share of sludge burned in Canada may reflect the higher proportion of the industry there that is kraft production. Kraft mills generally have hog fuel fired boilers in which sludge may be burned when mixed with hog fuel.

Sludges have also been used as soil conditioners or cover for landfill sites, while a variety of more exotic alternative uses have been investigated, including the manufacture of lightweight aggregate, recovery of fillers for use in papermaking, conversion into ethanol through hydrolysis. However, these alternative disposal options have not made significant inroads on traditional disposal methods.

Landfilling of Sludge

Public issues of the 1990's are forcing reexamination of the traditional cost effective landfill approach to the disposal of sludges and solid wastes by the industry. These are shrinking landfill space, difficulties in siting new landfills, increasing regulation reflected in higher tipping fees, and the trend to recycling. As an indication of this trend in the municipal area, in 1991 the U.S. Environmental Protection Agency estimated that over 5 000 of the 6 500 municipal landfill sites in the U.S. would close within the next 20 years and half of those in the next five years (NCASI #615, 1991).

The latest pressure comes from the recent and rapid move to high rates of paper recycling, both to reduce the volumes going to municipal landfills and to extend virgin fibre supplies. Nine states have reportedly already set standards which require 40% recycled content in newsprint by 2000, while one will require 50%. Many other states are in the process of adopting legislated or voluntary recycled fibre requirements.

Between 1991 and 1995, it is estimated that the waste paper demand for newsprint production in North America increased from about 2.3 to 4.4 million tonnes - almost doubling in five years (Forrest, 1995). The use of recycled fibre has also grown rapidly in other pulp and paper products.

The widespread use of landfill disposal on company property is a reflection of the convenience and historically low cost of this approach. In the U.S. the average total reported cost (capital plus operating costs) of landfill sludge disposal in 1989 amounted to $6.40 per cubic yard, and ranged from less than $1 to $25 per cubic yard. Significantly, the average total sludge disposal cost for landfills constructed since 1985 was much higher, at $9.80 per cubic yard. At this level of cost, sludge disposal represents a significant expense for many mills, leading many to consider alternative means of disposal. In April 1996 NCASI sent out another survey to update its earlier study of solid waste management and disposal practices in the U.S. pulp and paper industry.

Municipal landfill disposal is an order of magnitude more costly, if indeed land is available and permitted for sludge disposal. Increasingly, there is concern with sole reliance on landfill disposal due to more stringent environmental requirements. Federal regulations in the U.S. now require testing of extractives from sludges destined for industrial landfills to determine if the sludges are to be treated as hazardous wastes because of the potential for toxic leachates from metals and organic compounds. Surveys (NCASI #587, 1990) have shown that concentrations are well below regulatory levels. Landfill disposal is a matter of Provincial and State Jurisdiction, and special regulations may apply. Rules govern ongoing ground water monitoring, leachate collection and treatment, soil cover, lining, and in the case of new sites require significant permitting lead time and effort. More recent concerns relate to the dioxin issue and long term liabilities associated with landfilling.

For these reasons there has been renewed interest in land application, composting and combustion processes for sludge disposal in the pulp and paper industry generally.

Land Application

Disposal of sludges by land application, though not widespread, has been successfully used in North America and Europe for some time. It has the merit of recycling nutrients to the soil. Applications are in agricultural and horticultural crop production, silviculture applications, land reclamation, capping of landfill sites and land erosion control. Recycling of waste materials back to the soil dates back to earliest times. It is interesting to note that fully 29 % of the municipal sewage sludges in the U.S. are land applied.

The benefits are improved soil conditions which assist root development, plant nutrition and germination rates due to the increased porosity and water retention. Also the organic content is increased, which builds nutrient reserves and immobilizes metals due to the higher humus content.

This has led to regulations by the EPA, and numerous States, as well as Provinces in Canada (Quebec, Ontario and British Colombia) that define the maximum concentrations of elements and compounds in sludges, their application rates and permit requirements. It is noted that a number of regulated metals such as copper and zinc, in fact, are micro-nutrients required at low concentrations by plant life. Inks are considered to be a primary source of these constituents, and concerns have led to a decline in the use of cadmium, lead and chromium in ink formulations over the years, though copper, barium and calcium remain common. Heavy metals are persistent and will accumulate if applied to soils and not removed by plant uptake. Complex, stable organic compounds in soils chelate and render relatively inert metal contaminants. By maintaining a healthy bacterial population in the soil to recycle organic compounds, and by maintaining a high and stable level of humus, soils have a fairly high capacity to immobilize heavy metals.

Land application hinges on sludge characterization because it determines the nutrient levels, fibre and ash content, heavy metals, toxic contaminants of concern, pH buffering capacity, impacts relating to salinity and odour potential. Comparisons of published analyses shows high variability, even among mills of a given type due to the mill specific nature of raw materials and processing details, and underscores the raw material and process specific nature of sludge characteristics. Definitive characterization requires tests from each mill.

Odour problems arise if the decomposition process is allowed to become anaerobic. The best way to prevent this is to aerate the soil by cultivation, avoid spreading during seasons of high rainfall and provide a buffer zone adjacent to urban development.

Chlorinated organics degrade slowly because of their stable chemical structure and some are toxic to micro-organisms. This compromises the biodegradability of sludges and may be a further impediment to the general use of bleached kraft pulp mill sludges in food chain crop production. The EPA proposed a rule in 1991 that would limit the most toxic isomers of PCDD/F, tetrachlorodibenzo-p-dioxin and tetrachlorodibenzofuran, in soil to 10 parts per trillion (Campbell,1991). This rule was not approved as a Regulation, but evolved as an agreement between the EPA and the industry.

Other considerations in evaluating and costing land application as a means of utilizing sludge are the application method, whether the land is dedicated or not, and seasonality which will define the sludge storage needs or alternative method of disposal. Permitting of sludge application programs to date in North America has involved establishing the soil loading that is acceptable for a particular end use which then defines the application rate (ODt/ha) for a defined period of years.

An alternative way of facilitating the disposal of sludge receiving attention today is by composting. Composting is an accelerated aerobic, controlled biodegradation process that stabilizes the material, reduces the volume and weight and makes nutrients more readily available to plants. Composted pulp and paper mill sludges when mixed with bulking agents and fertilizers can be a soil substitute or amendment sought after by farmers, greenhouse operators, nurserymen and government departments. However, the composting approach is only justified if a market can be found for the product.

Composting has been undertaken on a limited scale in the municipal solid waste field as an alternative to landfilling. The issue of quality is generally addressed in terms of heavy metals content, inclusion of foreign particles and particle size. Quality standards have been established by several jurisdictions in North America and elsewhere, though on different bases. In several states in the U.S., the "risk-to-humans" assessment approach to guidelines is used. In Western Europe and now in several provinces in Canada (British Columbia., Quebec, Ontario), and some U. S. States, the "zero-net-increase" approach has been adopted, which means that no metals can be added to the soil beyond that removed by plants. The latter standards result in application levels of 1/5 to 1/10 of the risk-based guidelines (Timmenga, 1991). In the province of British Columbia, draft guidelines provide for several levels of quality depending on the end use, such as food chain-related, to forestry, and land reclamation uses where access by the public is more limited.

The simplest approach to composting is the setting up of wind rows, but the land requirements are substantial. A variety of commercial systems are available for composting which reduce space needed. Pilot plant studies are essential to establish the practicality of composting and prospects for the product.

Sludge Burning

The merits of burning mill sludges are volume reduction and energy recovery, provided moisture content is sufficiently reduced. It is the carbon content of the cellulose, lignin and biological sludges that contributes almost all the exothermic heat and hence the potential fuel value of sludge. Both wood fibre and biological treatment waste sludge contain close to 50 % carbon by weight on an ash-free basis. In practical terms of generating steam, the maximum amount of moisture must be removed prior to firing. While belt presses are a big improvement over vacuum filters and capable of 30 - 40 % solids content, it is screw presses introduced in the last decade that have made attainment of 40 - 50 % or more solids typical for most combined primary and secondary sludges and dramatically improved burnability of sludges.

In North America, in an integrated mill situation, dewatered sludge is often added as a slip-stream to the bark being fired in a grate type bark boiler, provided it represents a small side-stream of the total grate fuel.

For grate equipped boilers, the upper limit for the proportion of sludge in the total grate fuel appears to be about 30 % where ash levels are moderate and aggregate fuel moisture is no more than 55%. This limit is only attainable where the boilers include improvements such as 340 °C combustion air, modern overfire air systems to ensure good turbulence and gas mixing in the furnace, additional refractory and water cooled grates. Retrofits of water cooled vibrating grates with rebuilds of the overfire air system are relatively commonplace, and can lead to dramatic improvement in the amount of sludge burning that older boilers can do on a day-to-day basis.

For non-integrated mills, that is, paper mills without adjacent pulp mills and therefore without a wood refuse fired boiler common in chemical pulp mills, fluidized bed technology would now be selected in most cases for the dedicated sludge-burning operation because they can burn up to 100% sludge. This vastly improved ability to burn sludge is due to the large mass of the fluid bed material and its high heat capacity and the resulting very high rate of heat transfer in the bed. As a result there is a trend towards the adoption of fluidized bed technology in lieu of grate-type boilers in the North American pulp and paper industry following the earlier strong swing by the industry in Europe.

Circulating fluid beds are now seen as most appropriate for use on larger units and high heat content fuels such as coal. Bubbling bed types tend to be used for the smaller scale industrial applications with fuels of lower heat content such as sludge. Retrofitting bubbling bed type fluidized bed furnaces to existing grate-type power boilers and recovery boilers converted to power boilers has also been carried out at an increasing number of mills.

Mill Residues

Types of Residues Considered

Mill residues are the byproducts generated by a variety of wood processing plants such as sawmills, plywood and veneer mills, pulp and paper mills, particleboard mills and oriented strandboard plants. These residues include bark, sawdust, shavings, slabs, trim ends, chip fines, reject chips, sanderdust, and log yard debris. Pulp quality chips are explicitly excluded from the category of mill residues, given their high value as fibre.

Sawmills are the largest single source of mill residues in North America. Excluding wood, residue yield factors for sawmills vary widely, according to sawmill technology, product mix, log size, etc. In older sawmills, typically 20% or more of the wood input may be converted into residues (including sawdust, shavings, trim ends and yard waste), decreasing to as little as 13% in newer mills. The bark yield also ranges considerably, depending on the method of harvesting, sorting, and tree species.

Generally speaking, however, bark yields from milling operations for softwood species in North America amount to at least 10% of the volume of wood processed.

Mill Residue Physical and Thermochemical Characteristics

Physical and thermochemical properties of mill residues vary widely, reflecting the diversity of wood species, regional climatic variations, and harvesting, transportation, and processing alternatives found in North America. These characteristics are summarized in Table 2-5 and are briefly discussed below.

<u>Mill Residue Moisture Content</u>: While bark and green sawdust typically have an average moisture content of about 50%, water-soaked logs may yield residues with moisture contents in excess of 65% - an obvious candidate market for the dryers considered in this study. Planer shavings and other residues from kiln-dried lumber, on the other hand, may have moisture contents in the range of 8 to 19%, requiring no additional drying. In any event, these residues typically have a much higher value as fibre than as fuel.

<u>Mill Residue Particle Size Distribution</u>: To facilitate handling, bark is typically reduced in size in a hammer mill (or “hog”) to less than 75 mm (3") maximum dimensions, prior to being burned as “hog fuel”. A three-year study of hog fuel characteristics at the Harmac Pacific kraft pulp mill at Nanaimo, British Columbia (Warren, 1995), yielded the following information about particle size distribution (by dry weight):

Particle Size Range (mm)	% of Total Hog Fuel
75 - 5.5	33%
5.5 - 1.65	45%
1.65 - 1.18	12%
1.18 - 0.58	4%
<0.58 (fines)	6%

The foregoing hog fuel was obtained from a wide variety of mill sources, and was generated primarily from Douglas Fir, Western Hemlock with Amablis Fir, and Western Red Cedar.

Mill Residue Heating Value: The higher heating value of mill residues on an oven dry basis varies among North American tree species, but varies particularly among barks. For example, the HHV of Red Alder is only 18.6 GJ/ODt, versus 25.0 GJ/ODt for Lodgepole Pine bark (Nielson, 1985). On average, the HHV of wood is about 20 GJ/ODt, while that of bark is about 21 GJ/ODt.

Ash Content: The mineral matter (ash) content of clean wood species in North America typically varies from 0.1% to 0.6%, while that of bark ranges from 3% to 5% (Appel, 1993). Residues from the log yards of mill may contain large fractions of mineral matter which may pose slagging problems if the residues are used as fuel. A variety of processing systems (including air knife and water separation systems) are now being implemented to remove mineral matter from log yard debris and allow the recovery of chippable fibre, while yielding a byproduct wood residue fuel of acceptable quality (Mensch, 1995).

Table 2-5
Estimated Mill Residue Supply and Disposition ('000 ODt/a)

			Wood Residues		
United States (a)	**Total Residue**	**Bark**	**Coarse**	**Fine**	**Total**
Total Supply	100,513	26,049	45,517	28,947	74,464
Disposition:					
Fibre products	38,039	277	33,427	4,336	37,762
Fuel	40,642	18,366	6,898	15,377	22,275
Other Uses	16,188	6,015	3,345	6,828	10,173
Unutilized	5,645	1,392	1,847	2,406	4,253

			Wood Residues		
Canada (b)	**Total Residue**	**Bark**	**Sawdust & Shavings**	**Other**	**Total**
Total Supply	18,441	8,410	7,099	2,932	10,031
All Uses	9,876	3,493	4,161	2,223	6,384
Unutilized	8,565	4,918	2,938	710	3,648

SOURCES:
(a) U.S. Department of Agriculture, Forest Service, North Central Forest Experimental Station. Forest Statistics of the United States, 1992 (metric units). General Technical Report #NC-168.
(b) Canada: H.A. Simons Ltee. Biomass Prospects for Future Electrical Generation Plants: A Canadian Perspective. Prepared for the Canadian Electrical Association. CEA No. 9230 G 969. 1994.

Salt Content: Logs which are transported or stored in the ocean may absorb substantially quantities of salt amounting to 0.4% to 1%+ of the dry weight of the material, compared with the normal level of <0.1%. Mill residues generated from such logs and utilized as boiler fuel may cause corrosion in boilers if they are not specifically designed for high salt levels.

Mill Residue Quantities Available

Mill Residue Quantity in the United States. As detailed in Table 2-5, it is estimated that about 100 million ODt of mill residues were produced in the United States during 1991, of which only 5% was unutilized. The largest single end-use of mill residues was as Fuel (40% of total supply), followed closely by Fibre Products (fibreboard and sawdust-based kraft pulp) with 38%. Other Uses (16%) are not specified, but would likely include bark mulch for landscaping, livestock bedding and other agricultural uses. Coarse Wood Residues are primarily utilized for fibre products, while the majority of bark and fine wood residues are claimed by fuel-using applications.

Mill Residue Quantity in Canada: It has been estimated that about 18.4 million ODt of mill residues was produced annually in Canada, of which 9.9 million ODt was beneficially used (mostly as fuel or fibre), and 8.4 million ODt was disposed of through means such as incineration or landfilling (H.A. Simons Ltee., 1994). A considerable portion of the foregoing inventory was based on 1989 data, and since that time the surplus volume has shrunk substantially through the increased use of wood residues, both as power plant fuel and as fibre for various composite panel products and kraft pulp. The unutilized bark production was estimated at about 4.4 million ODt, or more than half of the total mill residue surplus. Over 60 % of the surplus Canadian wood residue quantity was concentrated within the province of British Columbia. A breakdown of Canadian mill residue production, use and disposal is provided in Table 2-5.

Future Mill Residue Production

The quantity of mill residues produced in the future will depend on the amount of timber milled times the coefficient of residues generated per unit of timber milled. A recent report (Haynes et. al., 1995) projects that the total harvest from U.S. forest land could increase from about 513 million cubic meters in 1991 to 717 million cubic meters in the year 2040 (a 40% increase), under the base scenario. Total softwood and hardwood lumber production in the U.S. could increase from about 48 million board feet in 1990, to 63.3 million board feet in the year 2040 (a 32% increase), under the base scenario.

There is opportunity for substantial improvements in lumber recovery factor (LRF) over time, as the present industry average LRF is far below that of state-of-the-art mills. By way of illustration, if the LRF were to increase from 250 to 310 feet board measure per cubic meter of logs milled, then total sawmill residue production would shrink by about 35% per unit of lumber produced, or 20% per unit of logs milled (H.A. Simons Ltd., 1994). In other wood-using industries the potential for reducing mill residue generation is judged to be much less than in sawmills.

Overall, it is considered likely that the 40% increase in the U.S. timber harvest will more than offset the average reduction in residue yield coefficient. The bark component of the mill residue coefficient per unit of timber processed is expected to remain fairly constant over time, resulting in a large increase in bark production if, indeed, the timber harvest increases to the extent projected. Whitewood residues are expected, in any event, to increasingly be used in higher value applications, rather than as fuel.

Alternative Uses and Costs of Mill Residues

The cost of obtaining mill residues for fuel use varies widely, as it depends on the regional competition for residues and the cost of transporting the residues from producer to user. The range of recent mill residue prices is illustrated in Table 2-6, which follows. It presents prices for western U.S. and Canada, circa December 1995, and is based on a regular and comprehensive industry survey. It should be emphasized that such prices may be quite changeable over time, reflecting the dynamics of supply and demand factors, including sawmill output, product prices in fibre-using industries, fossil fuel prices, etc.

It should be noted that U.S. residue prices are specified delivered to the user, while Canadian prices are F.O.B. sawmill bin. Residue prices at the low end of the range in the U.S. would be representative of situations where there is a minimal transportation cost.

Shavings are shown to command an average delivered price of $39/ODt in the western U.S., or $1.95/GJ, given a typical HHV of 20 GJ/ODt (8600 Btu/ODlb). The average delivered sawdust price in this region is not much less expensive at $33/ODt, or $1.65/GJ. Prices of this magnitude are driven by the value of the wood residues in fibre applications. Only in the northern interior of British Columbia are sawdust and shavings available from sawmills at a zero mill gate cost in some instances, and this situation is likely to change during the next few years with several large MDF plants expected to come on-stream.

It is expected that the diversion of sawdust and shavings to MDF and other fibre uses will increasingly decrease the fuel quality of wood residues used in existing power boilers, eventually leaving them mainly with bark, log yard debris, and sludge, all of which are fairly high moisture content fuels.

Hog fuel in the Western U.S. is considerably less costly than sawdust or shavings, at $19/ODt, or $0.95/GJ delivered to the user. The low end of the price range for hog fuel is shown to be in the order of $5/ODt ($0.25/GJ), which indicates that little or no mill gate price is being charged by the sawmills, given that the transportation cost alone is usually close to this amount. The British Columbia hog fuel price at the producing mill is also shown to be very low.

Mill Residue Seasonality

Generally speaking, the output of mill residues is fairly steady on a seasonal basis, given the tendency of sawmills to stockpile sawlogs during the logging season and operate throughout the whole year. Fluctuations in lumber prices and labor disputes, however, may cause occasional disruptions in supply of sawmill residues, although these may be mitigated to some extent by maintaining inventories of wood residues and the use of alternative fuels. There are several long-term supply factors affecting mill residue supply which are much more significant than seasonal variation. These include the level of sawlog harvest, improvements in lumber recovery, and competing non-fuel end uses.

Table 2-6
Sawmill Residue Prices, Western U.S. and Canada December 1995

Region	Shavings		Sawdust		Hog Fuel	
	Avg.	Range	Avg.	Range	Avg.	Range
	US$/ODt		US$/ODt		US$/ODt	
UNITED STATES (delivered to user)						
Washington						
Puget Sound	26	18 - 32	29	23 - 39	16	9 - 23
Northeast	29	27 - 33	29	26 - 37	18	14 - 23
Lower Columbia River	28	23 - 41	46	32 - 60	18	11 - 17
Oregon						
Willamette Valley	55	37 - 75	48	26 - 64	17	9 - 17
Northeast	48	44 - 55	20	14 - 32	17	11 - 22
Coast	28	17 - 48	32	28 - 43	17	9 - 22
South	50	29 - 60	44	35 - 50	16	13 - 24
California						
Coast	46	41 - 61	46	34 - 57	22	5 - 31
North	50	41 - 64	20	14 - 46	24	9 - 40
Central	48	37 - 60	20	14 - 44	21	9 - 28
Idaho	30	18 - 37	35	11 - 59	27	22 - 31
Montana	22	17 - 50	26	14 - 41	18	5 - 20
Average West U.S.	39	22 - 55	33	20 - 48	19	16 - 27
	US$/ODt		**US$/ODt**		**US$/ODt**	
CANADA (FOB mill bin)						
British Columbia						
North Interior	....	0 - 7	....	0 - 7	....	0 - 3
South Interior	11	7 - 15	11	7 - 17	....	0 - 3
Coast	15	8 - 19	15	8 - 19	....	0 - 3

Notes:

1 Prices from Wood Fibre Northwest, Market Report, December 1995, published by Wood Resources international Ltd., Bothell, Washington.

2 Converted from bone-dry units (BDU), as originally specified, to ODt on the basis of 1.09 ODt/BDU.

3 Canadian prices converted from Can.$, as originally specified, to US$ on the basis of 1.38 Can.$/US$.

Environmental and Regulatory Issues

Environmental and regulatory issues may act as either as incentives or disincentives to the use of mill residues as fuel, depending on circumstances in various jurisdictions.

While there may be some regional exceptions, in general it appears that the evolving deregulation of the electric power market in North America may diminish some of the previous incentives to use biomass as fuel. A large number of biomass-fueled powerplants have recently closed in the U.S., either as a result of contract buyouts by utilities, or the expiration of the 10-year high-price phase of Standard Offer 4. This situation is particularly evident in California where it is estimated that more than 250 MW of powerplant capacity formerly utilizing about 2 million ODt of biomass fuels, has closed in recent years (Morris, April 1995). As a result, the price of hog fuel is currently considerably below previous levels, which reportedly reached as much as $50/ODt during previous fuel price peaks of the early 1990's.

On the other hand, in British Columbia where a large concentration (roughly 4 million ODt) of mill residues currently exists, the provincial government has recently introduced regulations which will require all wood residue incinerators to meet a total particulate emission standard of 120 mg/m3 (B.C. Regulation 519/95). Under these regulations, it is expected that most existing incinerators will be shut down or upgraded by the end of 1997. At the same time, landfilling of surplus residues is generally prohibited as a means of disposal, except in special circumstances.

The life-cycle cost of constructing and operating a controlled wood residue incinerator which will comply with the foregoing particulate standard could approach $10/ODt for a typical sawmill. At the same time, the British Columbia government has announced that particulate matter discharge fees will be raised to about $72.50 per tonne by the beginning of 1997. In combination, these factors provide a strong incentive for mills to attempt to find beneficial uses for their residues, instead of incineration.

It was recently announced (April 1996) that two proposed wood residue-fueled cogeneration plants at British Columbia pulp and paper mills had been selected to enter into final negotiations to secure power contracts with B.C. Hydro. Together, the two projects would have a total generating capacity of about 59 MW and consume about 350,000 ODt of wood residues (mainly bark) annually, or about 10% of the unutilized provincial surplus.

If current trends continue, it appears that the increased manufacture of particleboard and sawdust-based kraft pulp in the future may claim a substantial portion of the presently unutilized sawdust and shavings in British Columbia. Though bark is used in a variety of non-fuel applications, (decorative ground cover, soil conditioner, road construction base material, etc.), these markets are limited, and it is expected that bark will remain in surplus supply in some regions, particularly in the interior of the province. Two sawmills in B.C. are reportedly considering the drying of residues as part of their disposal plan.

Logging Residues

Types of Logging Residues Considered

Following logging, a variety of residues are left on the forest floor or at landings, where logs are processed and accumulated prior to being transported to various types of mills. While most logging residues (tree tops smaller than the prescribed utilization standard, branches, and foliage) fall into the "non-merchantable"category, some "merchantable" components (such as broken tree trunks, cull logs with a considerable proportion of decay, and over-height stumps) as may also be left on site, depending on market conditions and regional logging regulations. The definition of logging residues may vary substantially among jurisdictions, so care must be taken when attempting to compare estimates of logging residue quantities.

The volume of logging residues generated per unit of wood harvested (or per unit of area logged) varies widely among regions, along with their size distribution, and energy value according to site conditions and terrain, species mix, age class, logging methods, and utilization standards and market conditions at the time of logging. Over time the coefficient of total logging residues generated has declined as utilization standards have tightened, wood values risen, and old-growth forests decreased as a proportion of the total harvest. Given this potential variability relative to the large size and diversity of the North American study region, it is necessary to rely on existing compilations of forest residue production.

Logging Residue Physical and Thermochemical Characteristics

Since logging residues consist of both bark and wood, their characteristics will fall somewhere between the values of these two constituents. Logging residue moisture content will typically average 45 to 50%, bulk density about 300 kg/m3 (wet basis), higher heating value about 20 GJ/ODt, and ash content about 1 to 1.5%. Ranges for each of these parameters are shown in Table 2-1. A detailed discussion of wood residue fuel properties is provided in recent report (Wiltsee, 1995).

Logging Residue Quantities

Logging Residue Quantity in the United States

Estimates of the quantity of logging residues generated annually in the U.S. vary widely among sources.

U.S. Forest Service: The U.S. Forest Service estimates that the total volume of logging residues generated in the U.S. during 1991 been was 97.8 million m3 (USDA, 1992), which equates to about 39 million ODt, assuming a density of 0.4 ODt/m3. About 40% of this quantity consists of growing stock volume cut or knocked down during harvest, but not removed from the logging site. The remaining 60% includes dead and cull trees, tops above the 10 cm growing-stock top, and trees less than 12.5 cm diameter at breast-height, excluding stumps and limbs. About 50% of the total estimated logging residue quantity is generated in the U.S. South.

University of Idaho: Johnson and Folk (1995) of the University of Idaho, on the other hand, estimated that about 109.5 million ODt of logging residues were available in the U.S. during 1991 - about 2.8 times the quantity estimated by the U.S. Forest Service! This discrepancy is attributed by Johnson and Folk to the definition of logging residues and the factors used to estimate the residue. About 58% of the foregoing quantity was estimated to have been generated in the U.S. Southeast. The average logging residue generation coefficient in the foregoing estimate amounts to 0.275 ODt/m3 of timber harvest.

Regardless of which estimate of logging residue quantity is used, it is apparent that the amount is very large. Perhaps more important that the sheer quantity of logging residues generated, however, are factors influencing the availability for fuel use, including cost, competition, and environmental issues, as discussed later in this section.

Logging Residue Quantity in Canada

An estimate of recoverable logging residue production in Canada was prepared by H.A. Simons Ltee. in October 1994 for the Canadian Electrical Association. This study estimated logging residue generation on the basis that 70% of the non-merchantable portions of merchantable size trees might be recovered, allowing for losses during the collection process. At current levels of harvest, total Canadian logging residue is estimated at 21.4 million ODt per year, of which 12.3 million ODt is at roadside and 9.1 million ODt is on the forest floor. More than 40% of the total Canadian logging residues are generated in the province of British Columbia.

A field survey of logging residues generated in Canada by 19 different combinations of stand types and logging systems (full tree versus tree length), found that total residue generation ranged from 0.09 to 0.41 ODt per cubic meter (m3) harvested, and averaged 0.21 ODt/m3 (Sylversides, 1981, cited in H.A. Simons Ltee., 1994).

Future Logging Residue Production

Logging residue production in the future will obviously be a function of the total volume of timber harvest times the coefficient of residues left on-site per unit of timber harvest. A recent report (Haynes et. al., 1995*)* projects that the total harvest from U.S. forest land could increase from about 513 million cubic meters in 1991 to 717 million cubic meters in the year 2040 (a 40% increase), under the base scenario. The hardwood share of the harvest is projected to grow from about 39% in 1981, to 42% by the end of the forecast period.

The same report indicates that softwood logging residues in the U.S. decreased from 10% of timber product removals in 1970, to 7.5% in 1991 - a 25% reduction. Future reductions in softwood logging residue quantities are expected to be much smaller, with logging residues projected at 7.1% of softwood timber products removals by the year 2040. For hardwoods, the coefficient of logging residue reduction over the period from 1970 to 1991 has been even more dramatic, dropping from 19.7% to 12.0% of timber product removals. By the year 2040, hardwood residues are projected to decline to 9.3% of timber product removals in the U.S.

If the foregoing projections are realized, the net impact will be a continuing and substantial increase in the total quantity of logging residues produced annually.

Alternative Uses and Costs of Logging Residue

Wood chips command a much higher price as fibre than as fuel, and this relationship is not expected to change in the foreseeable future. New equipment has been recently commercialized to remove the bark from smaller, irregular pieces of wood prior to chipping. Tests of the Deal Processor and Fuji King debarker have demonstrated their ability to debark log yard residue, small diameter trees and tops, frozen wood and decadent cedar chunks to produce chips with less than 1% bark content (Araki, 1995; Peetso, 1995). Mountain Fir Chip Company's chipping plant in The Dalles, Oregon, has purchased such equipment to allow the production of higher-value pulp quality chips from material such as orchard prunings or logging residues.

The Simco/Ramic Pulpwood Sorter, based on technology originally developed for the food processing industry, is another example of new technology which has been developed to upgrade the value of chips from fuel grade to pulp grade. It has been shown to remove about 75% of the bark or stained wood from off-specification chips, with a 75% to 80% recovery of pulp quality chips (Araki, 1995).

These factors will likely result in the majority of logging residues being utilized as pulp chips if and when they are eventually exploited. However, a portion of this material, including bark, chip fines, and off-specification chips, will be available as fuel as a byproduct from operations recovering logging residue for fibre. Such residues were used to fuel some power plants in California in the past, but with the surplus of fuel that currently exists in the area, logging residue recovery for energy has been reduced.

Logically, residue concentrations close to roadsides or landings would be the first to be utilized for energy purposes. Reflecting the diversity of site conditions and residue characteristics and processing and transportation options, estimated logging residue processing costs vary widely.

A recent study by Johnson and Folk (1995) concluded that recovery of landing residues after harvest could generally be carried out at lower cost than concurrent recovery of residues with logging of the site. By contrast, Longview Fibre, which is engaged in the recovery of logging residues on a commercial basis, finds it more economical to collect residue chunks in large containers during logging and truck them offsite for chipping. The company currently has 15 trucks and 150 chunk boxes dedicated to the recovery of logging residues in this manner.

Johnson and Folk estimate that the cost of recovering landing debris with an average diameter of 6 inches after the primary harvest ranges from a low of less than $26/ODt (large drum chipper, 80 km haul in 12 meter chip van), to a high of about $83/ODt (small whole-tree chipper, 80 km haul in 23 m^3 dump truck). Transportation costs account for about $17 and $56 per ODt of the foregoing total costs, respectively.

Even at the low end of the projected logging residue cost spectrum, it is difficult to justify the use of logging residues for fuel when a surplus of mill residues exists in many regions. Some powerplants in California are still obtaining a portion of their fuel requirements from forest residues, reportedly at costs as low as $30/ODt. However, a large portion of logging residues will only be available at much higher cost.

Logging Residue Seasonality

In swampy northern areas of the continent, equipment accessibility to logging areas is often restricted to the winter freeze-up period, while in areas with high snowfall, processing of residues will be considerably more difficult in wintertime. Summer shutdowns of logging activity may also occur as a result of high fire hazard conditions. These factors could make the availability of logging residues less regular than mill residues, since they often have a substantial stockpile of on-site logs.

Environmental and Regulatory Issues

Aside from economic considerations, concerns about nutrient recycling, erosion control, wildlife habitat, and moisture conservation may also discourage the removal of logging residues from the site. In the fall of 1995 a state referendum seeking to ban the removal of logging residue from harvest sites (as well as seeking to ban clear cutting itself) was put to Maine voters (NBIA, 1995).

On the other hand, the removal of logging residues and thinnings may be encouraged (or eventually mandated) in some jurisdictions, such as California, in order to reduce fire hazard. Given the diversity that exists among forest regions and individual logging sites in North America, however, it is virtually impossible to generalize about such issues. Smaller residues (branches and foliage) are most expensive to harvest and will likely be left on site in any event for environmental reasons, including nutrient recycling.

Peat

Type of Peat Considered

Peat is a heterogeneous mixture of partially decomposed plant matter and inorganic minerals that have accumulated under anaerobic conditions in shallow aquatic basins. This environment allows the retention of carbon and oxygen that would normally be released as gaseous products of biological decay. Most peat deposits have formed since the last ice age about 10,000 years ago, although much older deposits are know to exist. Peat is a precursor of lignite and coal deposits (Bolen, 1993).

While there several major peat classification systems used in various countries, peat is categorized as follows by the U.S. Department of Agriculture Soil Conservation Service (cited in Bolen, 1993):

- Fibric (peat moss) - composed of sphagnum and other mosses, this type of peat is used primarily in horticultural applications;
- Hemic (reed-sedge) - formed from reeds, sedges, swamp plants and trees, this type of peat has a high value as fuel, given its level of carbon fixation and low ash content;
- Sapric (humus) - composed of materials which are decomposed beyond recognition of botanical origin, sapric peats typically have higher ash contents which reduce their value.

In order to meet the U.S. Department of Energy’s definition of fuel-grade peat, the following criteria must be met. First, on a bone-dry basis, the material must be less than 25% ash by weight and must contain 18,568 kJ/kg (8,000 Btu/lb). Also, the peat deposit must be more than 1.5 meters thick and cover an area of 35 contiguous hectares.

Physical and Thermochemical Characteristics of Peat

As previously noted, peat is not a homogeneous substance, but the average higher heating value of fuel-grade peat typically ranges from about 19 GJ/ODt to as 21 GJ/ODt, on a dry weight basis. Ash content of sedimentary peat may reach 39%, but in fuel-grade peat, ash is generally in the range of 2 to 10% (Tarnocai, 1984). Bulk density (wet basis) ranges from as low as 170 kg/m3 for milled peat, to as high as 240 kg/m3 for sod peat (H. A. Simons, 1994). The moisture content of in-situ peat may range from 85% to 95%. After drying and processing, the moisture content of milled peat is generally reduced to about 50%, and that of sod peat to about 35%. Other properties of peat are detailed in Table 2-1.

While peat may be harvested by either wet or dry methods, the dry methods are more commonly used. These involved the draining of bogs prior to harvesting peat, either in the form of milled (pulverized) or sod peat. In both cases the peat is spread out on the site for a period of time to allow natural evaporation to reduce the moisture content to an acceptable level - typically 35% for sod peat and 50% for milled peat (Tarnocai, 1984), although the moisture content may be considerably higher. Given such high moisture contents, peat used to fuel utility boilers in countries such as Finland and Ireland is commonly dried using flue gas.

Peat Resources

Peat Resources of the United States

In the U.S., peat resources are estimated to cover more than 21 million hectares and to amount to about 71 billion tonnes, on an oven-dry basis (Burns and Roe, 1983 - *primary source cited as "Peat Prospectus, U.S. DOE, July 1979*). Peat resources are concentrated in Alaska (51%), Minnesota (14%), Michigan (9%), Florida (6%), and Wisconsin (5%). Alaskan peat reserves exclude peat located in permafrost regions where mining would be impractical.

While the potential resource base for peat in the U.S. is very large, the reserve base permitted for exploitation is only 4.1 million tonnes, and could theoretically be depleted within the next 20 years unless additional areas are permitted (Bolen, 1993). Peat production in the U.S. has fallen from about 1 million tones in 1987, to 0.6 million tonnes in recent years. The decline in production has been attributed to a variety of factors, including regulatory constraints on peat land exploitation, the large-scale recycling of yard wastes and other natural organic materials, and record-level peat imports from Canada. About half of total U.S. peat consumption is now imported from Canada.

Florida and Michigan accounted for about two-thirds of total U.S. peat production. On a weight basis, reed-sedge peat was 66% of total output; humus, 16%; sphagnum moss, 13%; hypnum moss, 4%, and other forms, 1% (Bolen, 1993).

Peat Resources of Canada

Deposits of peat are widely distributed throughout Canada, covering 12% of the land area, or about 112 million hectares in total. The largest areas of peat land are found in the Northwest Territories, Ontario, and Manitoba. While in-depth inventories of peat resources have not been carried out in all regions of Canada, it is estimated that about 335 billion ODt of peat exist, nationwide (Tarnocai, 1984). However, it should be noted that much of this quantity would not meet the previously-noted fuel grade specifications. Furthermore, about 60% of the total peat land area is perennially frozen.

Provinces which have carried out in-depth assessments of peat resources include Newfoundland, Nova Scotia, New Brunswick, and Quebec. More detailed information about provincial peat resources is provided in a 1994 report by H.A. Simons.

In 1994 Canada produced about 1.1 million tonnes of peat, primarily sphagnum peat for horticultural and agricultural uses. Quebec and New Brunswick are the two largest peat- producing provinces, together accounting for about 60% of shipments. About 75% of Canadian peat production is exported, primarily to the U.S. (Bergeron, 1994).

Alternative Uses for Peat

In North America, the exploitation of peat has largely been restricted to use in its natural state in agriculture and horticulture to condition clay soils, to maintain moisture in sandy soils, and to add organic matter and fertilizers to depleted soils. The availability of abundant and accessible fuels such as wood, coal, and oil and gas throughout much of North America has resulted in peat remaining virtually unutilized as an energy source, even though it is relatively abundant in many regions. These fuels are relatively inexpensive to extract and have high energy densities (per unit or weight and bulk) which make them much more transportable than peat.

Four 80-megawatt peat-fueled power stations had been planned in Florida, with the first unit slated to begin service in mid-1995. At full output, these plants would have required about 2.3 million tonnes of peat annually (Bolen, 1993). However, Florida utilities have since decided that it is more economic to generate power from natural gas, so development of these peat fired plants did not proceed.

A 22.8 MW peat-fueled powerplant at Cherryfield, Maine came on-stream in mid-1989, but has experienced both technical and financial difficulties. At full capacity, this powerplant was projected to require about 135,000 ODt of peat annually (Bolen, 1993).

Peat also has potential in a number of other applications, particularly its use as a sorbent for oil and toxic wastes, and as a filtration source in wastewater treatment.

The average price (f.o.b. plant) for bulk reed-sedge peat sales in the U.S. during 1993 is reported to be $20.26 per tonne as shipped (Bolen, 1993). Assuming an average moisture content of about 50%, this equates to more than $40 per ODt. Given a higher heating value of 20 GJ/ODt, this amounts to about $2/GJ, although this peat is not presently used for fuel purposes.

Environmental and Regulatory Issues

An major constraint to the large-scale utilization of peat for energy conversion is the environmental impact of peat mining. Given the relatively thin layers in which peat may occur, a very large area can be required to sustain the fuel needs of a powerplant. For example, it has been estimated that for a 300 MW powerplant utilizing a peat deposit with an average depth of 5 feet, moisture content of 35%, and heating value of 13,926 kJ/kg (as fired), more than 12,500 hectares of peat land would be required over a 30-year lifetime (Burns and Roe, 1983).

Peat mining may produce a variety of significant impacts on water and air quality, vegetation and wildlife. In terms of impacts on water resources, the removal of peat reduces the runoff detention storage of the natural ecosystem, tending to increase peak runoff. Changes in water quality such as increases in suspended solids, organic carbon (increased biochemical and chemical oxygen demand), inorganic nutrients, and changes in pH. Fugitive dust emissions from peat harvesting and storage also represent a significant potential impact on air quality. While a variety of measures may be employed to mitigate some of these impacts, the mining of peat for large-scale fuel use fundamentally alters large areas of natural ecosystems, and may be unacceptable where other fuel alternatives exist.

As previously noted, declining peat production in the U.S. has been partially attributed to increasingly onerous environmental regulations. Since 1986, 37 peat mining operations have been idled or gone out of business. Large areas containing peat resources have been set aside for environmental protection by Federal and State agencies in coastal Virginia and North Carolina (Bolen, 1993).

Lignite

Lignite Physical and Thermochemical Characteristics

Lignite is the lowest rank of coal, with a low heating value and high moisture content. Its moisture content sometimes reaches 45%, and the coal tends to disintegrate when exposed to weather. The HHV of lignite, as received, ranges from about 10 to 20 GJ/tonne and averages about 16 GJ/tonne (DOE, Feb. 1995). Given the low heating value of lignite, it cannot be economically transported as far as higher rank thermal coals. Most lignite in North America is therefore used to fuel power plants located close to lignite mines.

Characteristics of lignite from mines in North Dakota are summarized in Table 2-1.

The high moisture content of lignite is disadvantageous in several ways:

- It increases the transportation cost per unit of heating value;
- It reduces boiler efficiency;
- It causes derating when burned in boilers designed for higher rank coals;
- It causes freezing of coal in railroad cars in cold climates, such as in North Dakota.

For these reasons, there has been considerable interest in lignite drying in some jurisdictions (Bechtel Corp., 1993). However, to date most lignite utilized as fuel in North America is burned without drying.

The thermal drying of lignite causes it to crack and crumble during handling, reducing particle size and creating dust which can be a major nuisance during shipment, handling, and storage. The application of heavy oil to dried lignite has been found to provide a significant benefit in dust control and reduction in wind losses during transport (Nowacki, 1980).

North American Lignite Reserves

Lignite Reserves of the United States

In the U.S., lignite reserves have been estimated as follows:

Demonstrated Reserve Base (DRB): measured or indicated (but not inferred) deposits, at least 60 inches thick, that can be surface-mined. Also includes thinner and/or deeper beds that presently are being mined or for which there is evidence that they could be mined commercially at the time of inventory. As of January 1, 1992, it was estimated that 43.3 billion tonnes of lignite were included in the DRB in the U.S. (DOE, Feb. 1993).

Recoverable Reserves: that portion of the in-place demonstrated reserve base that is estimated to be recoverable at the time of determination. Estimated recoverable lignite reserves in the U.S. as of January 1, 1992 totaled 33.6 billion tonnes (DOE, Feb. 1993).

Regardless of which definition of lignite reserves is employed, it is clear that enormous quantities of lignite are available, relative to the quantities of other potential feedstocks considered in this study. About 28% of recoverable reserves are located in Texas, and 20% in North Dakota.

Production of lignite in the U.S. during 1994 totaled about 80 million tonnes. Texas and North Dakota are the dominant lignite-producing states, with 59% and 37% of national output, respectively. Mine site prices of lignite during 1994 averaged $8.40/tonne in North Dakota, and $13.56/tonne in Texas (DOE, 1994).

Lignite Reserves of Canada

In Canada, large lignite reserves are located in Saskatchewan, with smaller deposits in British Columbia, Ontario, and Alberta. Estimated reserves of lignite coal in mineable seams in Canada as of December 1985 totaled about 2.8 billion tonnes (Smith, 1989), while recoverable lignite reserves were placed at 2.2 billion tonnes. "The term coal reserve refers to that portion of the resource which is anticipated to be mineable under technological and economic conditions prescribed by a feasibility study, and which has no legal impediment to mining." (Smith, 1989). As such, lignite reserves form only a portion of total measured, indicated, or inferred resources.

Lignite reserves include both Lignite A (14.7 - 19.3 MJ/kg) and Lignite B (< 14.7 MJ/kg), specified in terms of HHV on a moist mineral-matter-free basis. A total of 10.7 million tonnes of lignite were produced in 1994 (Shapiro and Lomas, 1995), virtually all in Saskatchewan where lignite is used to fuel three generating stations for Saskatchewan Power Corporation and several others in Manitoba and Ontario. The characteristics of Saskatchewan lignite are quite similar to those of North Dakota lignite.

Bagasse

Bagasse is the fibrous residue from sugarcane after the cane has been harvested and crushed to extract the juice. The quantity and quality of bagasse vary with the type and age of the cane, as well as the nature of the harvesting and milling processes. For each green tonne cane that is harvested, the yield of bagasse is in the order of 0.11 to 0.14 tonnes, on a bone-dry basis. Bagasse is typically produced at a moisture content of about 50%.

Sugar cane production in North America is limited to Florida, Louisiana, and Texas. Total sugar cane production in the U.S. during 1995 is in the order of 26.3 million tonnes. Florida accounted for 51% of this total, followed by Louisiana, with about 30%, Hawaii with 14%, and Texas with 5% (USDA, National Agricultural Statistics Service, 1996).

Applying a coefficient of 13% to the national production figure of 26.3 million tonnes of cane, yields an estimate of about 3.4 million ODt of bagasse. Given its origin as a byproduct of sugar cane, bagasse production is quite seasonal.

The largest use of bagasse has been as fuel for steam production in sugar factories. However, it may also be used in a wide variety of other applications, including the following:

- as a source of fibre for paper and paperboard products;
- as animal feed (mixed with molasses and a nitrogen supplement);
- as a mulch and soil conditioner;
- as poultry litter.

Physical and thermochemical characteristics of bagasse are detailed in Table 2-1. While bagasse is dried in some mills prior to use as fuel, it usually is burned without drying. Bagasse drying was not practiced at all in the sugar industry until 1975 when it was introduced as an energy conservation measure. A paper by Kinoshita (1991) describes the experience with flue gas drying in Hawaiian sugar plants. Three of the four factories discussed in this paper utilize rotary dryers, while one installation has a flash dryer.

In the continental U.S., bagasse is not usually dried prior to burning. Two large bagasse-fired cogeneration plants, developed by a limited partnership of Flo-Energy Corp. (an affiliate of Flo-Sun Inc., a large sugar company) and U.S. Generating Company have recently come on-stream in Florida. One of the plants has the capacity to produce 70 MW of power, reportedly the largest sugar mill cogeneration plant in the world (International Cane Energy News, July 1994), while the other plant has a capacity of 55 MW. About two-thirds of fuel requirements will be met by bagasse, and the remainder from wood waste. Bagasse does not store for long periods without deterioration of its fuel value, so many bagasse-fired cogeneration plants rely on a supplemental fuel such as wood waste or coal during the off-season when bagasse is not being produced as a byproduct of the sugar mill.

Significantly, neither of these state-of-the art bagasse-fired cogeneration plants dries its fuel prior to burning it. The decision not to incorporate dryers was apparently based on concerns about dryer cost and operating reliability.

3

EFFECTS AND BENEFITS OF THERMAL DRYING

Basic Principles

Combustion temperature is one of the key parameters in the good combustion of fuel, with residence time and gas turbulence also important drivers of the process.

The amount of moisture entering a furnace with wet fuel has a significant effect on the combustion process. A fuel drying operation before the furnace greatly improves combustion since drier fuel burns hotter and more vigorously. The impact of this improved combustion are wide ranging. Most important among these effects are reductions in: the amount of fuel used to meet a given thermal requirement; the sizing and cost of some of the fuel handling, boiler and emission control equipment; the use of sustaining fossil fuel when this is normal practice. Some of these effects are quantifiable from basic concepts and are presented next, while others require more detailed discussion and are presented later in the section.

Combustion of fuel in a furnace, and the subsequent recovery of heat from the gaseous products of combustion involve complex processes of chemical reactions and kinetics, fluid mechanics and heat transfer. However, useful insight is gained on the fundamental role of moisture in combustion if we limit our view to four basic parameters: adiabatic flame temperature, specific flue gas volume, boiler efficiency and specific steam generation. Table 3 - 1 presents the effect of % moisture content wet basis on each of these parameters for a typical pulp and paper mill sludge, a relatively clean wood residue and a lignite using the typical analyses for each.

Adiabatic temperature

Adiabatic temperature is the theoretical temperature the air and fuel would reach if the combustion were completed adiabatically, that is, with no heat loss to the surroundings. Though actual temperatures reached in the hottest zones in a furnace are typically several hundred degrees less than this due to heat radiation and gas mixing, the adiabatic temperature is still a useful parameter for two reasons. First, it serves as a guide to the ease with which a fuel can be burned. Secondly, it can be determined by calculation from the elemental analysis of the fuel, its moisture content, and conditions of the combustion air, namely, its temperature and percent excess air.

Experience in designing and operating grate equipped furnaces indicates that the adiabatic combustion temperature must be maintained above 1100 - 1400 °C for adequate control and burnout of fuel particles. This is higher than the temperature threshold for fluidized bed furnaces where a minimum adiabatic flame temperature of 1050 - 1100 °C is required. The result is that the tolerable moisture content of fuel is greater for fluidized bed furnaces than for grate equipped furnaces. This is due to the mechanism of heat transfer to the fuel which is by conduction rather than radiation and convection.

From the data in Table 3 - 1, sludge is seen to present problems once the moisture content exceeds 50% and approaches 60% for grate equipped boilers and somewhat above 60% for fluid bed boilers.

Volume of Flue Gas

The volume of flue gas generated by the combustion process is affected by the moisture in the fuel, being significantly larger when the fuel is very wet. To illustrate this, the actual volume of wet flue gas generated per oven dry amount of fuel, which we call Specific Flue Gas Volume, is presented in Table 3 - 1 for a nominal stack temperature of 150°C. This parameter is important from the point of view of sizing of the boiler and emission control equipment in new designs; in existing furnaces and boilers, it determines the velocity in the gas passages where boiler tube erosion may be a critical limitation.

Boiler Efficiency

Boiler efficiency determines the amount of useful heat that can be recovered from burning fuel. It is normally calculated by quantifying the source of heat lost from the fuel burned in a boiler. The principal losses are due to:

- flue gas or stack losses, which is the total heat carried out of the boiler by the flue gases. It is the sum of the heat in dry products of combustion (CO_2, N_2, etc.), the heat in the water vapour arising both from the water in the fuel and the water formed by the reaction of the hydrogen in the fuel. The magnitude of this loss, which varies widely and depends particularly on the moisture in the fuel, is typically in the 10 - 40% range;
- the unburned carbon in the fuel leaving with the grate and fly ash, which is typically in the 1 - 5% range;
- Radiation losses and Manufacturers Margin which is typically in the 1 - 5% range.

From the data in Table 3 - 1, Boiler Efficiency is seen to drop off rapidly after 40 - 50% moisture content.

Steam generation

The useful heat recovered in a combustion process is directly related to boiler efficiency. To illustrate this, in Table 3 -1 we present the specific steam generation, or the amount of steam generated per oven dry amount of fuel, as a function of moisture in the fuel, assuming steam generation at 6300kPag /450°C (900 psig/840°F). Typical

Table 3-1
Effect of Moisture on Key Combustion Parameters(a)

	Unit	**Moisture Content, % wet basis**					
		0	**20**	**40**	**50**	**60**	**80**
Adiabatic Flame Temperature							
Sludge	°C	2200	1810	1470	1290	1090	530
Wood Residues	°C	2190	1830	1500	1340	1160	640
Lignite	°C	2160	1800	1480	1320	1150	640
Specific Flue Gas volume at 150°C							
Sludge	$Am^3/ODkg_{fuel}$	7.6	9.3	11	13	14	20
Wood Residues	$Am^3/ODkg_{fuel}$	9.2	11	13	15	17	23
Lignite	$Am^3/ODkg_{fuel}$	9.6	12	14	16	17	24
Specific Flue Gas volume at 150°C							
Sludge	$Am^3/ODkg_{fuel}$	17	20	25	28	31	45
Wood Residues	$Am^3/ODkg_{fuel}$	20	25	30	33	37	50
Lignite	$Am^3/ODkg_{fuel}$	21	26	31	34	38	53
Boiler Efficiency							
Sludge	%	83	78	70	64	55	11
Wood Residues	%	83	76	72	68	61	24
Lignite	%	85	80	73	68	61	26
Specific Steam Generation							
Sludge	t/ODt_{fuel}	5.1	4.8	4.3	3.9	3.3	0.7
Wood Residues	t/ODt_{fuel}	6.3	5.7	5.4	5.1	4.6	1.8
Lignite	t/ODt_{fuel}	6.4	6.1	5.5	5.2	4.6	1.9

Note: a - Inerts content dry basis taken as: 20% for sludge, 0.5% for wood residues, and 27% for lignite. Carbon content dry basis taken as: 40% for sludge, 50% for wood residues, and 51% for lignite. Sludge is from a kraft pulp mill. Combustion air preheated to 300°C.

Improvements in Boiler Performance

- This section identifies and outlines the principal advantages of fuel drying technologies which are:
- more flexible boiler operation using less or no support fuel
- improved thermal efficiency
- increased steam generating capacity (debottlenecking) or physically smaller boiler plant equipment for new units
- reduced gas velocities and potential for erosion of boiler tubes
- reduction in most air emissions
- reduced fan power

and then describes the operating disadvantages that may potentially result:

- furnace ash slagging
- increases in some air or liquid emissions
- decreased availability

Improved combustion provides more manageable boiler operations and gives the boiler increased ability to follow changes in steam demand. In cases where it is used, fossil fuel usage is reduced or eliminated. Boiler thermal efficiency is also increased, though in the case of a low cost or waste fuel, this is not the economic advantage that it is with an expensive fuel.

There is no limit to the degree of dryness for suspension firing. However, there is a maximum dryness for grate firing as the combustion temperature approaches the ash fusion temperature. When this temperature limit is exceeded, slagging of ash on the grate will occur. For fluid bed combustion as drier fuel is fired, steps must be taken to remove heat as the combustion temperature approaches the ash fusion temperature. When this temperature limit is exceeded, slagging of ash will cause defluidisation of the bed, requiring furnace shut down.

The degree of improvement in boiler performance that can be expected through external drying depends to some extent on the type of grate used in the boiler. The older styles which include fixed or pin hole grate, travelling grate, or steeply sloping fixed grate are less capable of handling very wet fuel and the benefits of external drying is more marked. With the newer water cooled vibrating or multi-slope inclined grates, the use of hotter combustion air and drying zones on the grate improves the ability of these boilers to burn very wet fuel, and the benefits of drying externally to the furnace are less marked. Examples of water cooled vibratory grates are Detroit Stoker's Hydrograte and Kvaerner's (formerly Gotaverken) bare tube panel sloping and reciprocating foot grate.

More flexible boiler operation

With drier fuel, a hotter, more vigorous combustion, the burning rate is higher which improves the responsiveness of the boiler to changes in load and fuel quality. In cases where support fuel was previously used to facilitate control, this may be reduced or eliminated. Combustion temperature is the key element in the good combustion of fuel, with time and turbulence also driving the process.

For grate-type boilers, the adiabatic combustion temperature must be maintained at 1400 °C or above for adequate control and burnout of fuel particles according to one authority (Kraft, 1991), and 1093 °C or above according to another (McDermott, 1980). Knowing the moisture content and elemental analysis of a fuel allows one to calculate the adiabatic temperature. The burning of fossil fuels will make up for inadequate dryness in the wet fuel, though with a significant operating cost penalty for each percent moisture increase.

Drier fuel on the grate is more likely to encourage the development of a hot uniform fuel bed able to handle the inevitable variations in fuel moisture and physical properties seen in practice which can range from wood chunks, to free flowing solids, to wet sludge cakes.

In the case of wetter sludges where there is insufficient drying area on the grate, blanketing of patches of the grate and buildup of unburned fuel can occur. The colder, slower burning patches on the grate then cause uneven distribution of undergrate air , which further aggravates the problem, making load following and boiler control difficult or impossible. The operational response is the continuous use of sustaining fossil fuel. For this situation, drying such wet fuels externally to the furnace results in a boiler which is much easier to operate.

For fluid bed-type boilers, the tolerable moisture content of fuels is somewhat higher than that for grate burning because the mechanism of heat transfer to incoming sludge is by conduction rather than radiation and convection. In addition, the large mass of bed material in relation to fuel, where the fuel represents only a very small fraction of the bed mass, provides a thermal flywheel effect capable of absorbing uneven fuel slugs and variations in moisture, inerts and fibre. A significantly lower minimum adiabatic flame temperature of 1050 - 1100 °C is acceptable (Kraft, 1991) (Louhimo, 1990). Fluid bed furnaces therefore do not normally require external drying of wet fuel, as modern cost and energy efficient dewatering systems such as screw and drum presses are able to attain the moisture content levels required to achieve these adiabatic temperature, which is about 45% - 55% moisture but also depends on the inert content of the fuel.. At the other extreme, very dry fuel may cause excessively high bed temperatures with attendant problems caused by ash melting and bed defluidisation, requiring flue gas recirculation. It is noted that one of the steam dryer technologies to be described later on, the mixing bed dryer, avoids this problem by self-regulation, since the heat for drying is removed from the bed material itself.

Improved Thermal Efficiency

External drying results in a gain in thermal efficiency. This is accomplished by reduction of boiler heat losses, and in certain cases, recycle of drying heat back into the system which is facilitated in steam drying technology to be described in the next section.

The reduction of boiler heat losses is in three areas, though the most important of these is reduced flue gas heat loss. The second is the reduced excess air required for effective combustion control due to the more vigorous combustion. Finally, the amount of unburned material leaving with the grate ash and fly ash will be reduced for a given boiler because of the faster burning rate.

Reduced Flue Gas Heat Loss

Flue gas losses are the product of both the mass of gases released to the atmosphere and the temperature at which they are released.

Flue gas dryers reduce these losses generally by lowering stack temperature, not by reducing flue gas mass flow. This contrasts with steam dryers which reduce the flue gas loss by reducing the flue gas mass flow as the fuel moisture is not returned to the stack. In addition, the flue gas temperature may be reduced as well with steam drying for reasons explained further on.

For a flue gas type dryer applied in a retrofit situation, the exiting boiler combustion gases are directed to the dryer where they are further cooled in performing their fuel drying role before release to the atmosphere. Here, the dryer acts as an additional heat transfer surface in the boiler. The reduction in flue gas heat losses is solely due to the lower temperature, since the water removed in the dryer is returned with the flue gas to the stack. This mass flow is identical to the flue gas mass flow for the same boiler without a dryer.

For a new boiler installation designed with a flue gas type dryer, the temperature of release of the flue gas is a matter of design optimisation. If the temperature selected with a dryer and without is the same, the stack losses will be identical. However, the dryer represents low cost heat transfer surface if its double function is taken into account, and corrosion aside, the design with a dryer would favour selecting a lower stack temperature than otherwise would be the case.

The second category, the steam dryers, provides lower stack losses through reduced flue gas mass flow, but not necessarily through reduced stack temperature. The reduction in mass flow is due to the moisture in the fuel which is not returned to the stack gases.

The uncertainty in temperatures arises because, in an existing boiler installation, the stack temperature depends on the redistribution of temperatures in the furnace that results. The drier fuel raises the adiabatic temperature, reduces the mass flow, affects the volumetric flow rate and flue gas residence time in the various boiler internal passages. These temperature changes occur in the furnace exit gas, and in the convection sections of the boiler and back passes, all of which influence the stack temperature, and determine that component of the flue gas losses.

In the case of the independently heated dryer such as a rotary type dryer where part of the dried wood is used as fuel for a separate heater supplying the dryer, the reduced flue gas losses is not obvious by inspection either, as two flue gas streams are involved, each with its own mass flow and temperature.

Reduced Excess Air

In practice, the amount of excess air over a practical minimum is a matter of operational convenience or preference and management tolerance of the thermal inefficiency and higher fuel bills that result. The practical minimum level of excess air is governed by the stoichiometry of the fuels fired, fuel moisture, boiler load and swings in relation to design capacity, and air emission limits. Though operation at much higher levels of excess air is common, particularly for wetter fuels, a number of literature sources suggest some very approximate levels based on experience.

Some typical levels of excess air representative of reasonably achievable good practice for burning wood waste are presented in Table 3 - 2.

Table 3-2
Range of Percent Excess Air - Good Current Practice

Moisture Content, %	(Linderoth, 1986)	(MacCallum, 1981)
10 - 20	25	20
30	30	28
40	40	34
50	60	38
60	100	43

A rough rule-of-thumb is to assume a % excess air equal to the % moisture in the fuel wet basis.

Reduced Unburned Carbon Loss

The amount of any unburned material leaving with the grate ash will be reduced for a given boiler because of the more rapid combustion rate on the grate resulting from fuel drying. The loss of unburned material associated with the fly ash can also be expected to be reduced because of better carbon burn-out for two reasons: the longer residence time and hotter temperatures.

However, in the case of fuels with a high fines component, carryover may increase with the drier fuel since it will be lighter, so that component of the unburned carbon loss is not assured. For this reason, fuel for grate type boilers is generally dried to no more than 25% moisture content.

Increased Steam Generating Capacity or Smaller Boiler plant Equipment

Existing Units

For existing grate type boilers, the limitation on steam generation capacity with wet fuel normally arises from the excessive carryover resulting from the use of high levels of excess air mostly directed undergrate as the firing rate is increased. Wetter fuel requires a higher proportion of combustion air directed undergrate so as to promote fuel drying and burning on the grate. The consequent reduction in overfire air tends to decrease char burnout. This increases the load on the particulate emission control equipment and may result in air emission permit exceedences. Normally, combustion air and induced draft fans are generously sized and are not the first limits encountered.

A less immediately apparent limit for both grate and fluid bed-type boilers, as firing rates are increased above design in existing units, is boiler tube erosion. This occurs due to the excessive flue gas velocities in the narrow gas passages between tubes in the generating bank. This is a serious problem because of the cost of boiler tube replacement and the downtime necessary. Erosion will occur if the boiler is burning fuel containing much more moisture or sand than it has been designed for. To some extent, erosion can be mitigated by adding curved erosion shields to the upstream portion of the tubes.

With drier fuel, the steam generation rate can often be increased to 5 - 15% or more above the rated maximum continuous rating (MCR) or nameplate design on wood fuel in many cases, because introducing less moisture into the furnace reduces gas flow velocities in the narrow gas passages just described. This is also because the limitation on steam generation rate is normally not driven by the water side design of natural circulation boilers, the type virtually universally used in industry, because of very conservative design criteria traditionally adopted. However, once the steam flow limit of the drum is reached, or the superheater pressure drop is excessive, it is not cost-effective to go beyond the original MCR. For many wood and other solid fuels, boiler sizing traditionally has often provided higher MCR for fossil fuel firing, which may allow some opportunity to stretch capacity.

New Units

New unit designs for dried fuel are largely determined by the selection of design criteria considered appropriate for the fuel, the furnace type and firing method. Here we will limit discussion to three criteria that impact on the cost of a new unit and which are affected by firing drier fuel, as compared with fuel containing the moisture as received. These are:

Grate Heat Release The amount of wood fuel that can be successfully fired on a given grate is limited. This limit is expressed in terms of gross heat release per unit area. The release rate is closely linked to the upward flow velocity of flue gas above the grate which is normally limited to about 6 m/s to avoid excessive carryover (Babcock and Wilcox, 1992). Grate heat release is the product of the mass rate of grate fuel fired and the heat content of the fuel divided by the grate area. Whether computed on a dry or a wet basis, the parameter is the same. This criteria applies to grate equipped boilers and to a lesser extent to fluidized bed boilers, and suspension firing. The general recommendation of the main manufacturers is a value of 3150 kJ/m^2/s (1 000 000 Btu/h/ft^2) for fuel moisture of 50% or less for sizing of grates for the burning of solid fuel. For higher moisture fuel, the heat release rate would be less. For instance, at 60% moisture a heat release rate of 2700 kJ/m^2/s (850 000 Btu/h/ft^2) would be used. Of significance for this study is that the heat release rate limit is seen as independent of fuel moisture once the dryness is below 50%.

These release rates contrast with some data in the literature where grate heat release ranges from 2500 to 3800 kJ/m^2/s (800 000 - 1 200 000 Btu/h/ft^2), depending on the grate type and manufacturer's recommendations (Spurrell, 1984). In one case, a converted recovery boiler operates at a grate heat release of 4640 kJ/m^2/s (1 470 000 Btu/h/ft^2) (Barsin, 1988). However, the anomaly this latter case apparently presents may be explained by the very generous furnace sizing of recovery boilers necessary for successful for black liquor firing. This would compensate for a small grate where much of the fuel would be entrained by the undergrate air, but because of furnace volume would have time to burn out. Normal economic furnace proportions dictate for reasonable control of carryover as one of the main constraints of grate sizing. Another source, sales literature by Bahco, the Swedish manufacturer of the cascade dryer, now part of ABB, claim that grate heat release rate can theoretically be increased from 3150 kJ/m^2/s (1 000 000 Btu/h/ft^2) for fuel moisture of 50% to 3940 kJ/m^2/s (1 250 000

Btu/h/ft^2) for fuel moisture of 30%, provided the furnace can be optimised for this condition only.

Furnace liberation All furnaces, whether grate equipped, fluid bed or suspension fired types, require adequate furnace volume above the grate to complete the combustion process. Typical furnace liberation or volumetric heat release rates for wood like fuels are of the order of 175 kJ/m^3/s (17,000 Btu/ft^3/h). This volume is one control of furnace residence time, the other being gas temperature. Average gas and fine particle residence time should be in the 2 - s range to avoid carryover of unburned fuel from the furnace, and is determined by dividing the flue gas volume flow rate in m^3/s by the effective furnace volume in m^3. The flue gas volume flow rate is taken as the average of two temperatures: the gas temperature over the grate, and the temperature at the furnace exit (the plane of the first row of steam superheater/generating bank tubes).

Furnace gas weight This parameter, in large measure, determines the physical size of the superheater and steam generating banks, economizer, induced draft fan, emission control equipment and duct work, since the temperature levels through these elements are determined by criteria that remain the same whether fuel is dried or not. With temperatures essentially similar, furnace gas weight translates to equal gas velocity criteria in areas to limit erosion. The gas weight with drier fuel will decrease for two reasons: the higher efficiency of combustion will require less fuel on an oven dry basis, producing less flue gas; and with proportionately less water vapour in the flue gas, the weight will decrease further. For further information the reader is referred to the references (Babcock and Wilcox, 1992; Combustion Engineering, 1991).

In summary, in a new unit designed to meet a given steam generation, it is clear that drier fuel will result in a smaller furnace / boiler/ air emission control system because the higher efficiency of combustion will require less fuel on an oven dry basis, and gas weight will decrease. But a second effect of using drier fuel may be favourable shifts in design criteria. There seems to be reasonable grounds to expect a still smaller and less costly unit relative to undried fuel by virtue of selecting a higher grate heat release, and the lower furnace gas weight per unit of fuel fired giving a smaller boiler / economizer / fans / air emission control system. However, there may be some counteracting influence of the higher adiabatic flame temperature increasing the furnace size to limit excessive exit gas temperatures or NO_x emissions. Some idea of the savings based on a crude exponent scaling of the furnace gas weight ratio indicates that one designed for 30% moisture fuel is 15 - 20% less costly than one designed for 50% moisture fuel.

As many variables are involved, it is recommended that steam generation equipment suppliers be involved with the sizing and costing of boilers at the preliminary phases of projects, so that the fuel and site specific details of a proposed project can be reliably evaluated.

Reduced Fan Power

With drier fuel, power consumed by boiler fans is reduced because of the reductions in: combustion air flow; flue gas flow volume; system pressure drops for the same steam generation. The amount of power saved varies as it depends on the type of fan drive / volume control (variable frequency drive, inlet louvre dampers). However, given sufficient information, it can be readily estimated.

Operating problems

Furnace Slagging

Fouling or slagging which is the build up of furnace deposits can lead to thick coatings on furnace surfaces and even the plugging of flue gas passages. Heavy rates of deposition can drastically decrease boiler availability due to the need to take downtime for their removal.

With drying the fuel externally to the furnace, the likelihood of this occurring increases since the furnace temperatures generally increase. The slagging is caused by ash being at the temperature where it begins to exhibit stickiness which results in it attaching itself to cooler surfaces. This temperature is directly related to the ash fusion temperature, for which three threshold temperatures are conventionally defined: ash deformation, ash melting, and ash free flow.

The worst problems of slagging occur with fuels that contain the highest concentration of total ash and alkali metals, principally sodium and potassium. The situation can be made worse with the introduction of sulphur into the furnace if in sufficient quantities. A source is when firing heavy oil which often has sulphur contents of 1.2-2.5% by weight. Another common practice in the kraft pulp industry is the burning of odorous sulphur-rich in power boilers. The sodium and potassium components of ash are intrinsic to many biomass fuels as they are incorporated into the plant structure as they grow. This results in their appearance as fine fume while the surrounding cellulose and other organics pyrolyse and burn. Being elements with low melting points and forming eutectics with low melting points, they combine mechanically with sand and other higher melting point inert materials to form a matrix that when cooled is both tenacious, strong and difficult to remove.

Ash deposits may be caused by one or a combination of factors:

Inert contaminants in the biomass fuel

Study of the ash slagging properties in biomass fuels, though not as complete as that for coal, has produced predictive indices of slagging potential as a function of ash analysis.

One simple measure of whether fouling is likely to occur is the ratio of alkali metal oxides to silica: $(Na_2O + K_2O) / SiO_2$. As a rough rule of thumb, indices above 2 indicate fouling potential; below 0.3, erosion is more likely a concern. Another indicator is the onset of sticky ash temperatures. Some individual analyses that may not be representative of average values are presented in the Table 3 - 3.

Table 3-3
Selected Ash Fouling Indices and Ash Deposition Temperatures

Fuel	Ash Fouling Index [(a)] $(Na_2O + K_2O) / SiO_2$	Deformation, Softening / Melting, Fluid Temperature [(a) (b)], °C
Demolition wood	0.15	-
Pine bark, Construction wood	0.19	1190 / 1280
Western wood residues	0.42	-
Softwood bark	0.45	1180 - 1240 / 1385 - 1440
Eastern Hemlock	0.57	-
Tree prunings	1.4	-
Hardwood bark	7.4	-
Oak	7.9	1440 / 1450
Sunflower seed husks	23 - 37	940 / 980

Notes: a - (Appel, 1993) b - (Hupa, 1977)

Interaction with Contaminants in the fossil fuel

Sulphur in the fuel if in sufficient quantity to exceed the absorption capacity of the fly ash will result in the creation of sulphates and sulfites which form hard deposits (Hupa, 1982). Also vanadium found in some heavy fuel oil is enough to react in the furnace with sodium compounds to produce low melting point oxides and vanadates which have been well investigated and are known to contribute to plugging and corrosion.

Other factors that contribute to slagging are high carryover of ash from the furnace, high combustion and flue gas temperatures and boiler design aspects such as: poor sootblower locations, number, selection or sequencing; design of furnace elements, such as design heat release criteria, overfire air system design, superheater and generating bank configuration and metal temperature criteria, and tubular air heater.

Availability

For a boiler with high availability, the installation of a fuel dryer may decrease the overall availability of the boiler - dryer system because of the greater overall system complexity. Statistical data were not encountered during the course of the study on changes of availability with the addition of dryers. Obviously, the simplicity of a boiler without a dryer would ensure higher availability, unless firing drier fuel improved the reliability and operability of a boiler with low availability.

As boilers are generally required to have high availability, they would normally be designed to be able to operate with wet wood bypassing the dryer, and have sufficient fossil fuel firing capability to generate the balance of the steam needed to meet the situation when the dryer is not operating.

Effect on Air Emissions

This subsection discusses the effect on composition of combustion products, and on the contaminant loadings leaving the boiler due to the firing of drier fuel. The direct impact of the drying system on the contaminant levels in the flue gas after leaving the boiler, and their effect on the performance of down-stream emission control equipment is discussed in Section 4 - Assessment of Fuel Dryer Technologies.

Particulate

In the case of wood stoker fired grate type boilers, typically about 80 - 95% of the total inerts in the fuel is in the form of gas borne particulate, called fly ash or furnace carry over. The balance of the total ash residue stays in the furnace and leaves as grate ash. Fly ash is composed of intrinsic ash or the inerts in the clean fuel, sand contaminants introduced during wood and fuel handling, unburned char and salt fume, the latter usually only present where the wood has been immersed in sea water.

Besides fuel moisture content, combustion related factors affect carryover by determining the degree of burnout for the entrained char. These include plan and volumetric heat release rates, which directly affect furnace temperature and residence time. Char burnout is also governed by aerodynamic factors, such as furnace shape, overfire air jet geometry, fuel particle size distribution, char reinjection, the split of under grate to over grate air and combination firing (Adams, 1977). Char reinjection has a large effect in particulate emissions since it decreases average particle size and increases dust loading to the particulate emission control system by 20 - 100% (Levelton, 1978).

In fluidized bed combustion furnaces, the quantity of carry over is considerably less due to the virtual absence of char in the ash resulting from the high combustion efficiency, though all ash leaves the furnace as carry over. In the case of suspension burning, the ash carry over is also virtually 100%.

With grate firing, the particulate matter (PM) emissions leaving the boiler will be reduced after fuel drying in most cases. This is because of the reduced carry over of unburned material resulting from the higher combustion temperature and longer furnace residence time, as already discussed, which will increase burnout of the carbon. One exception is where fine material comprises a high proportion of the wet fuel which, once dried, may be too light to land and burn on the grate, but is immediately swept upwards and may not have sufficient residence time to complete burn out before leaving the furnace.

For fluid bed furnaces, PM emissions leaving the boiler are expected to be insensitive to fuel moisture level and fuel drying, because of the very low unburned carbon losses of these units, even with high moisture fuels.

In the case of retrofitting pulverised fuel suspension firing to a grate equipped boiler, PM emissions leaving the boiler are much higher than that produced by good grate firing, as all the wood ash leaves with the flue gas. Thus if existing emission control is by a mechanical collector, PM emissions would increase, both because of reduced flue gas flow, lower pressure drop and higher proportion of fine material in the ash. Accordingly, an electrostatic precipitator would probably be required to meet current best practice as reflected in the latest emission requirements for new facilities.

Nitrogen Oxides

NO_x is produced in all combustion processes and occurs primarily by two routes.

The first is the formation of NO from the high temperature reaction of atmospheric nitrogen with oxygen, a reaction that only occurs to a significant degree above 1400°C and is highly dependent on the flame stoichiometry (local excess air), and residence time of the reacting gases at the flame temperature. This formation route is called thermal NO_x.

The second route of formation is by the oxidation of chemically bound nitrogen in the fuel, by a complex mechanism, involving gas- and solid- phase reactions. This NO_x is called fuel NO_x, and depends primarily on the nitrogen content of the fuel, though flame stoichiometry and residence time at the flame temperature play a role.

High temperatures in the furnace cavity cause the reaction equilibria to favour the formation of nitric oxide, NO. For coal, N_2O is present at concentrations of the order of 100 - 200 ppm_{dv} at temperatures in the region of 800°C and decreases linearly to 0 - 5ppm_{dv} when furnace temperatures are about 925°C. From limited data, these N_2O levels appear to be two to three times less than those for wood and other biomass fuels at the same temperature (Brown, 1996). N_2O is a greenhouse gas with an effect comparable to methane. Furthermore, it is not detected with conventional NO_x continuous emission monitors.

As the gases cool on their way past the superheater, generating bank, and other heat transfer surfaces, the reaction equilibria shift to favour the formation of NO_2 from NO, though this occurs at a slower rate; N_2O does not undergo significant change. As a result, leaving the stack, the predominant form of NO_x is NO, with only about 5 - 10 % being NO_2, due to the kinetic limitations in the oxidation of NO to NO_2. Further generation of N_2O, however, can occur with selective catalytic reduction (SCR). SCR with ammonia results in the conversion of the order of 10% of the NO to N_2O; for selective non-catalytic reduction using urea, about 2 - 3% is converted.

With drier fuel, the higher furnace temperatures will tend to increase the formation of nitrogen oxides. This is counteracted somewhat by the reduced excess air levels used which hinders thermal NO_x formation. Of far greater influence than fuel moisture levels on NO_x formation is the design of the overfire air systems, where new systems with air staging in both grate-type and fluid bed-type boilers show markedly reduced NO_x formation than older designs.

When NO_x emissions from the firing of biomass fuel, even after drying, are compared with natural gas fired in conventional NO_x burners they are at similar levels of about 85 - 100ng/J, while when compared with oil and coal are likely to be significantly lower. However, low NO_x fossil fuel burners are an active area of development and some natural gas and oil burners are capable of very low emissions of the neighbourhood of 15 and 35ng/J for gas and oil fired burners respectively. This is significantly lower than what a conventionally designed biomass boiler is capable of, and lower than the 21 - 30ng/J touted for a recent boiler in the Pacific North West which was unable to meet this guarantee.

With drier fuel, the fluid bed temperature of the bed will increase and if it moves beyond the typical temperature of 700 - 900 °C into the range of ash slagging, measures such as flue gas recirculation or bed cooling by means of tube bundles may have to be taken to control bed temperature satisfactorily. These measures will limit any rise in NO_x emissions of fluid bed units.

By way of comparison, NO_x emissions from natural gas burners are comparable, but oil and coal fuels are likely to be significantly higher than that of biomass combustion, even after drying.

VOC and other Organics

Volatile organic compounds (VOC) are a loosely defined grouping of photo-oxidant compounds containing at least one carbon atom that are volatile and are of organic origin. Photo-oxidants exhibit chemical reactivity in sunlight and have a role in the formation of smog with attendant low level ozone formation. Because they have no role in smog formation, the VOC definition excludes carbon dioxide, carbon monoxide, methane and chlorofluorohydrocarbons. The group is also known as Total Gaseous Non-methane Organic compounds (TGNMO). The group is commonly expressed in terms of equivalent carbon or methane (CH_4).

VOCs can contain hydrocarbons such as ethane, ethylene, napthalenes, aromatics, alcohols, aldehydes, and volatile vapours of hydrocarbon liquids. Within the definition of VOCs, there are a number of other subsets of non-methane organic compounds. One identified by the US EPA are hazardous air pollutants (HAP) because of concern with their potential impact on human health. From a VOC point of view, total HAP are negligible when compared with other VOC components.

Man-made or natural volatile hydrocarbons combine with nitrogen oxides in the presence of sunlight, to form photochemical smog which contains ozone a strong oxidant. Such low elevation or tropospheric ozone, along with other photochemical oxidants, are the components of smog which are of potential concern. In locations where there are already significant NO_x and VOC emissions, meterological conditions can combine to create ozone and smog episodes of sufficient duration to be detrimental to human health, crops and vegetation.

The origin of the volatile organic compound emissions from boilers are the pyrolysis gases that evolve during combustion process of the wood or other fuel which have not been oxidized before leaving the furnace. For an existing unit, VOC are minimized by ensuring good gas mixing in the upper furnace volume, maintenance of furnace temperature and excess air. Firing drier fuel in an existing older boiler would contribute to the reduction of VOC levels, though more cost-effective control would be by installing a new combustion air system to provide better furnace mixing.

Drying of wet fuel externally to the furnace would also appear to reduce the emissions of dioxins and furans. A number of relevant technical papers have appeared (Luthe, 1993 and 1994; Välttilä, 1994) which describe tests indicating that dioxins and furan are formed in boilers when firing solid fuel containing chlorides or chlorinated organics even in small amounts, and propose strategies for their control.

The conditions favouring dioxin and furan formation are the presence of fly ash and residence time at temperatures in the 200 - 400°C range which are typically found in the back passes of boilers. To inhibit dioxin and furan formation and reduce these emissions, furnace design and operating conditions should be aimed at providing the total conversion of carbon to CO_2, and Cl_2 to HCl. In practice, total conversion is not achievable, but a number of strategies have been identified in furnace and equipment design aimed at furthering this objective which are:

- Maximize high flame temperature and minimize the carryover of char with the fly ash so as to avoid delayed pyrolysis of the char, which functions as a catalyst for the reformation (de novo synthesis) of dioxins and furans
- Maintain a high degree of gas turbulence in the furnace to avoid flue gas short-circuiting, channelling or chimney effects and maximize residence time in the furnace at elevated temperature to ensure decomposition of dioxins and furans and their precursors
- Cool the gases leaving the furnace as quickly as possible particularly through the 400 - 200°C range, minimize contact with soot, and provide a flue gas temperature leaving the air heater below 200°C to avoid reformation of these compounds.

Though the foregoing strategies for controlling VOC's involve a number of aspects of design and operation, external drying of wet fuels will be of benefit primarily by increasing char burnout and raising the combustion temperature. However, quantifying the amount of any reduction is not presently possible as test data is very sparse and no calculation procedure is believed to have established for this complex phenomenon.

4

ASSESSMENT OF FULL DRYER TECHNOLOGIES

Types

Thermal drying systems for the moist fuels are grouped according to the drying medium. The two principal categories considered here are:

- flue gas type
- steam type

Others types are indirect dryers and hot air dryers which are described briefly below.

Flue gas dryers use the sensible heat in the products of combustion to accomplish the drying and are well established technology. The heat supplied in the gases, together with the moisture driven off, is directed first to emission control equipment and then to the stack for release.

Steam dryers use the sensible heat in steam to accomplish the drying. The steam originating from the moisture driven off from the fuel is recirculated as the heat transfer medium. They are a more recent development, and come in a variety of forms.

The recirculated steam used by steam dryers is reheated to superheated conditions by an external source such as hot combustion gases, high pressure steam, hot bed material from a fluid bed furnace or by means of a steam compressor. The quantity of excess steam generated, equal to the amount of moisture driven off, is at a lower energy level than the heat supplied. Capture of the latent heat of vaporisation of the excess steam generated for use in the steam cycle where possible improves the thermal efficiency. This potential for greater efficiency distinguishes steam drying from flue gas drying and provides its potential advantage. The recirculation of steam also facilitates the capture of volatiles driven off during drying. As a result, it is steam drying which is a most active area of the development and growth currently.

Indirect thermal dryers, or thermal dewatering systems, use the heat in addition to mechanical stirring or pressing to reduce moisture content of the material. Equipment takes the form of rotating disks, coil assemblies or screws heated internally by steam. These types are well proven technologies in most cases, and are commonly used in dewatering sludges and pulps in the agricultural and animal feed industry, and are being introduced for drying municipal effluent treatment plant sludge. Some systems are capable of producing a very dry product. This capability is a significant advantage in cases requiring a dry product as it avoids a subsequent processing step for drying. However, being both dewatering and drying by conduction in one step, these systems are not treated in this report.

A schematic diagram of the flue gas dryer and the steam dryer is presented in Figure 4-1.

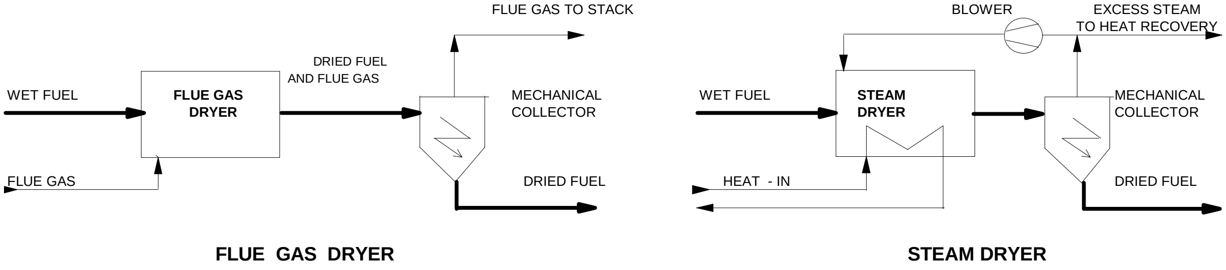


Figure 4-1 Flue Gas Dryer and Steam Dryer

For completeness, a final category, air dryers should be mentioned. These dryers use air heated by steam coils to dry the fuel, but are much less common now than other types. This technology was marketed by two manufacturers in the 1970s - 80s: Mekantransport AB of Sweden and Jeffrey Manufacturing of the US. This report does not treat air drying as neither system is being offered today.

Flue Gas Dryer

Drying Potential

The maximum reduction in the moisture content of wet fuel that can occur in a flue gas dryer is constrained by the heat available in the flue gas for drying and the amount and moisture of the as-fired fuel. This potential for drying can be approximately estimated for any installation where the gas quantity, moisture content, and temperature, fuel quantity and moisture content are known, using approximate values of specific heat of water vapour of 1.9 J/°C/g and dry flue gas of 1.0 J/°C/g. For studies where this information is not available, computer programs are used to determine flue gas quantities and composition from the as-fired wood and moisture content, and determine the heat available in the flue gases using the specific heats of each component, since the dryer and boiler computations are coupled and require an iterative solution for a given application.

For the simpler case, when a boiler is only fired by the wet fuel being dried, and all the flue gas produced is used to dry the fuel, the average moisture content of dried fuel is solely a function of the moisture content of the wet fuel entering and the decrease in the temperature of the flue gas across the dryer. Some results from calculations for the

100% wood fuel case based on a flue gas dryer exit temperature of 105°C are presented in Table 4 - 1.

Table 4-1
Potential for Drying Wood Refuse in Flue Gas[(a)]

	Initial Moisture in Fuel, % wet basis		
Flue Gas Temperature Leaving the Boiler Air Heater, °C	**100 °C**	**175 °C**	**260 °C**
Final Moisture in Fuel, % wet basis			
60	62	67	71
50	55	61	65
40	47	54	60
30	40	48	55

Note: a - based on 100% wood fuel firing and 105°C final stack temperature (MacCallum, 1981).

These results are somewhat optimistic, given the limitations that frequently apply to the selection of such a low flue gas dryer exit temperature.

The minimum dryer gas outlet temperature must be kept above the water vapour dew point to avoid corrosion by carbonic and, in the case of sulphur contained oil or coal, sulphurous and sulphuric acid. Corrosion of the dryer, ductwork and stack, if of carbon steel, is rapid if this temperature is too low, and sometimes dryers and downstream equipment is of stainless steel or fibreglass. Such is the case where sea water borne wood is fired, as the salt fume in the flue gas is particularly corrosive.

In theory, with low sulphur content fuels, such as wood, sludge, gas, the exit temperatures could be of the order of 60°C, but in practice, due to radiation loss and cold air infiltration in systems that are usually under negative pressure, dryer and stack temperatures are kept in the 90 - 120°C range. In cases where sulphur content is significant, such as in heavy fuel oil, exit temperatures must be above the dew point of sulphuric acid which is well above that of water. In such cases, dryer exit temperatures of 130 - 160°C may be required, which can reduce the potential for drying significantly.

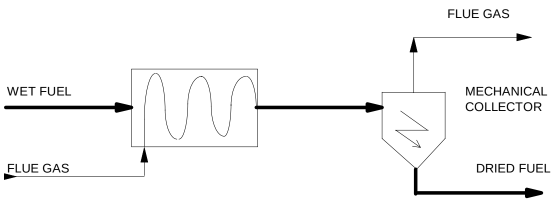
The maximum temperature that can be used at the dryer inlet is limited by the concern for fires. However, this temperature is generally above the burning temperature of dry wood in air of 260 - 290°C, since the flue gases are depleted in oxygen relative to air (typically 5 - 10% O_2 by volume), and in all systems the smaller particles, which dry most quickly, pass through the system rapidly. The maximum temperature used is about 320°C (608°F) with most systems, though flash dryers can use up to 430°C because of short residence time. Some manufacturers of dryers use dryer exit gas recirculation to temper the incoming hot flue gas and reduce the risk of fires.

Types

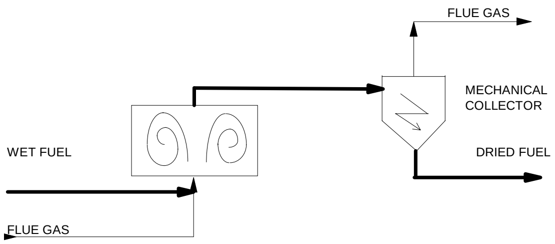
Three of the most common commercially available flue gas dryer types are:

- rotary, where the wet fuel particles move slowly along a cylinder where they are re-exposed to the gas stream by lifting flights;
- cascade, where the wet fuel particles enter a vertical vessel containing a swirling torus of fuel and flue gas;
- flash, where the wet fuel particles enter a vertical drying tube along which they are pneumatically conveyed by hot flue gases;

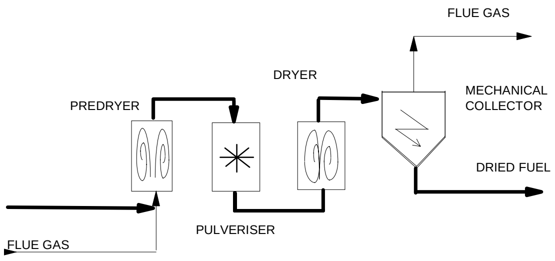
A schematic diagram of these types is presented in Figure 4 - 2.



ROTARY FLUE GAS DRYER



CASCADE FLUE GAS DRYER



FLASH FLUE GAS DRYER

Figure 4-2 Flue Gas Dryer Types

Rotary Type

Concept

The main components of a rotary drying system include an inlet section, a rotating horizontal cylinder, discharge section, cyclonic material separation equipment, dryer fan, emission control equipment, conveyors, and ducting.

In a rotary dryer, the fuel is in contact with flue gas and travels co-currently with it along the rotating cylinder. The mixing and contacting of the fuel and gas is assisted by internal longitudinal flights that lift the fuel up and let it shower down through the flue gas. Smaller particles are carried along rapidly, entrained by the gas flow; larger particles are moved more slowly towards the exit end. The drying process takes place in suspension, by radiation and also through direct contact between the fuel and the heated metal.

In the absence of flue gas, part of the dried fuel is used in a burner as a heat source.

The retention time for the smallest particles can be as short as 30s while for most of the material it is in the order of 20 - 30 minutes. Common design features affecting retention time include single and triple pass and dense versus open internal flighting. The single pass dryer is less prone to plugging and can handle a wider range of particle sizes; a triple-pass dryer uses concentric cylinders to increase the gas path length costs less. Some designs recirculate 55 - 65% of the flue gas to lower the gas temperature at the inlet to the dryer and reduce the generation of blue haze, fine particulate composed of the more volatile components of the material being dried, particularly problematic in the case of wood.

A significant limitation in all dryers is the non uniformity in product moisture content when drying a fuel with a large range in particle size, though rotary dryers with their long residence time do a better job.

Fans are required upstream and downstream as the dryer operates under slight negative pressure to limit dusting and to avoid excessive infiltration of air at the drum end seals. The discharged gas is taken to the dust separation equipment, normally large diameter cyclones, where the fines from the fuel are separated from the gas. The collected fines are either mixed with the larger material leaving the dryer or returned to the boiler for separate firing in suspension. The flue gases then receive further treatment in mechanical collectors (multiple cyclones), wet scrubbers or electrostatic precipitators.

Rotary dryers are suitable for materials which are in the form of free flowing solids and fibrous particles of up to 125mm (5"), granules, pellets, broken filter cakes and powders. As well, these materials must be moderately insensitive to heat.

Manufacturers

From among the numerous manufacturers supplying a very broad range of applications in a range of industries, M-E-C Inc, Rader Inc., Raytheon (Stearns-Roger Division), ABB Raymond (Bartlett-Snow) are particularly well represented in the forest products industry.

Applications

The rotary dryer is a mature technology and the work horse of the solids processing industry and is to be found in such diverse plants as those producing fertilizer, pharmaceuticals, lead and zinc concentrate, cement and agricultural byproduct and animal feed among many others.

To give an indication of the numbers of rotary dryers used for fuel drying and the recent sales activity for this type of application, an analysis of types of rotary dryer applications in the forest and paper industry was undertaken, based on an analysis of the installation lists provided by several suppliers. Other potential applications in peat and lignite drying were not discovered, though test drying of lignite using rotary dryers was carried out in the 1970s (Nowacki, 1980).

Numerous applications of rotary dryers have been made in the drying of sludges from municipal waste water treatment plants, but there are significant drawbacks. Relative to other sludge drying processes, the dryer produces large quantity of exhaust gases which contain odorous compounds as well as the moisture driven off the sludge. A number of rotary dryers have been shut down because of the difficulty of treating the odours (Black & Veatch, 1995).

The forest and paper industry applications are taken in their broadest sense, and includes pulp and paper, sawmills and board mills, the latter embracing particleboard, oriented strandboard, wafferboard, and medium density fibreboard. The results are presented in the table 4 - 2, and show a marked decline in sales for fuel and sludge drying in the last 5 years.

Table 4-2
Representative Applications of Rotary Dryers by Vendor

		M-E-C Inc	Rader Inc.	Raytheon
All industries		≈500	80	>300
Forest products and pulp and paper		318	62	-
Fuel drying	1980 - 1990	18	19	2
	1990 - 1995	2	4	0
Sludge drying (pulp and paper only)		1	4	-
	1980 - 1990	1	2	-
	1990 - 1995			

Capacities and Performance

Evaporation capacities are mostly in the range of 3 to 23 t/h corresponding to dryer sizes of 3 feet diameter x 8 feet to 13 feet diameter x 60 feet long. Two of the largest of 18.5 feet diameter x 85 feet long for a board mill in Quebec have been awarded in April 1996 have an evaporative capacity of 23 t/h.

One older reference provides information on nine representative rotary dryer applications in the form of tables provided by three manufacturers, ignoring the data from a fourth which is no longer in business (H. A. Simons, 1983). The information is supplied for pre-feasibility study purposes and is necessarily preliminary. The information is summarized in Table 4- 3.

Table 4-3
Typical Ranges of Design and Performance Data For Rotary Dryers

Evaporation		t/h	3 - 23
Capacity		ODt/h	3 - 45
Moisture content range, typical	feed	%	45 - 65
	discharge	%	10 - 45
Pressure drop		kPa	2.5 - 3.7
Particle size	optimum	mm	19 - 50
	maximum	mm	25 - 125
Thermal Requirements		GJ/t_{evap}	3.0 - 4.0

Cascade Type

Concept

The principal component of the cascade dryer is a short vertical vessel with conical bottom and top with flue gas entering the bottom and leaving at the top.

The wet fuel is introduced along with the flue gas, and a swirling torus of fuel and flue gas develops in the centre of the vessel. The lighter particles leave with the flue gas, the heavier leave through adjustable slots at the bottom of the vessel and are discharged by a rotary air lock. The fines leaving the dryer are removed from the flue gas by cyclones.

Moisture reduction is normally similar to that with rotary dryers, that is from 60 - 50% down to 40 - 20% range, wet basis. Retention time is in the order of 2 minutes. Hogging, undertaken to facilitate wood fuel handling, is sufficient size reduction for the cascade dryer.

Retrofitting a cascade dryer would require the addition of another fan downstream of the unit to handle the additional pressure drop of the dryer and cyclones. Normally no mechanical dust collectors are required upstream of the unit, unless the material contains more than 5 - 6% inerts dry basis.

Manufacturers

The original cascade dryer design was by Bahco of Sweden. Initially they served the North American market from Sweden. On 1 October 1984 the rights to the technology in the Americas were acquired by Midland Ross and subsequently the new parent company, Hercules. As of April 1988, the sales, design and manufacturing in the US, Canada and the rest of the western hemisphere has been by ESI Inc., of Kenneshaw, GA. The original Bahco group is now part of the ABB group which have retained the rights for the rest of the world.

Applications

The cascade dryer appears to only be used for wood waste, with none applied to bagasse, lignite or other solids. The progression of sales of cascade dryers over the years are presented in the next table.

Table 4-4
Numbers of Installations of Cascade Dryers for Wood Residues by Vendor

Bahco Installations to 1982 - Europe		19
Midland Ross / Hercules 1983 - 1988		6
E.S.I since 1988		2
	Total installed:	27

Capacities and Performance

The throughput rates and evaporation capacities and other design criteria and typical performance parameters are based on the same reference used for the rotary dryer section (H. A. Simons, 1983). This source provides information on four representative cascade dryer applications in the form of tables provided by the manufacturer at the time, Bahco of Sweden. The information is supplied for pre-feasibility study purposes and is necessarily preliminary. The information for the four cases includes: fuel inlet and outlet moisture content of 55% and 32%, flue gas inlet and outlet temperatures of 233°C and 93°C, and oven dry throughput's ranging from 1.4 to 24.5 ODt/h. The information is summarized in Table 4 - 5.

Table 4-5
Typical Range of Design and Performance Data For the Cascade Dryer

Evaporation		t/h	2 - 41
Capacity		ODt/h	1.3 - 25
Moisture content range, typical:	feed	%	45 - 65
	discharge	%	10 - 45
	typical feed, discharge	%	55, 35
Pressure drop		kPa	2.5 - 3.7
Particle size	maximum	mm	100
Thermal requirements		GJ/t_{evap}	2.7

Flash Type

Concept

The principal components of the flash dryer are the predryer duct, pulveriser mill, the classifier, flash dryer ducts, fines separator cyclone, and induced draft fan. If the particles to be dried are small enough to be suspended in the gas stream, the pulveriser would, in principle, not be required.

The wet fuel is metered into the predryer, a vertical duct where it is partially dried and conveyed by hot flue gas to the classifier. The classifier ensures that only oversize material is passed through the hammer mill where further drying occurs. From the classifier, the material is conveyed by the hot gases through successive vertically oriented flash drying ducts to a large diameter cyclone where the dry fuel is recovered and may be sent to storage or conveyed to the burners by primary combustion air. The flue gas is returned to the inlet of the emission control equipment which would typically be an electrostatic precipitator or other high efficiency system, since unlike the rotary dryer, particulate matter emissions would increase after passage through the flash dryer.

A simpler system used by ABB Raymond, without predrying consists of a mill and a classifier, which conveys dried material to the burners with the flue gas containing the additional moisture driven off from the fuel. Thus the mass flow through the boiler is not reduced as in other cases reducing the potential gain in boiler efficiency.

The final moisture is normally in the range of 10 - 20% wet basis.

Retention time is in the order of 2 - 10s, providing the potential for rapid response to control signals. Hogging, undertaken to facilitate wood fuel handling, is sufficient as a size step prior to the flash dryer.

Retrofitting a flash dryer would require the addition of another fan downstream of the unit to handle the additional pressure drop of the dryer and cyclones.

Manufacturers

One flash dryer design is by Flakt, of Sweden and now part of the ABB group. Also part of the ABB group, a second manufacturer is the Raymond Division of what was Combustion Engineering, now called ABB Raymond.

Ahlstrom of Finland have a flash dryer that they have been using on their wood gasifier plants which deliver low heat content gas for firing lime kilns. Contact with their representative in Washington indicates that they would quote dryer opportunities, particularly in biomass waste gasification applications (Mikkola, 1996).

Williams Patent Crusher and Pulverizer Co., Inc. of St. Louis, MI has a line of impact dryer mills which are used on lignite, coal and wood waste.

F.L. Smidth, of Denmark, also have a flash dryer technology which is combined with pulverized fuel firing of lime kilns: however, the process is no longer being offered (Theil, 1996).

Applications

The flash dryer is used not only for wood waste, but also for peat, bagasse, lignite or other solids. Installations of flash dryers on wood refuse are presented in the next table.

Table 4-6
Numbers of Installations of Flash Type Flue Gas Dryers on Wood Waste

	Flakt	Ahlstrom	Williams
Installations	6	6	2

Capacities and Performance

The throughput rates and evaporation capacities and other design criteria and typical performance parameters are based on the same reference used for the rotary dryer and cascade dryer sections. This source provides preliminary information on five representative flash dryer applications in tabular form, provided by Flakt.

The information for the cases includes: fuel inlet and outlet moisture content, flue gas inlet and outlet temperatures, for oven dry throughput's ranging from 6.4 to 16 ODt/h and evaporations to 17 t/h. The information is summarized in Table 4 - 7

Table 4-7
Typical Range of Design and Performance Data for Flash Type Flue Gas Dryer, based on ABB Flakt.

Evaporation		t/h	4.8 - 17
Capacity		ODt/h	4.4 - 16
Moisture content range, typical	feed	%	45 - 65
	discharge	%	10 - 15
	typical feed, discharge	%	55, 12
Pressure drop		kPa	7.5
Particle size	maximum	mm	0.5 - 50
Thermal requirements		GJ/t_{evap}	2.7 - 2.8

Costs

Capital Costs

Cost data was obtained from a number of sources in the literature. No supplier quotations were solicited.

The first kind of cost information needed is for the dryer equipment alone for the different types of flue gas dryer equipment: rotary, cascade, and flash. Dryer equipment supply and erection costs were obtained from a 1993 update (B. H. Levelton, 1993) of a 1983 study (H. A. Simons, 1983) received from Environment Canada which has not been officially issued. This information is presented as in the original source on a oven dry kg throughput basis rather than the more general evaporation basis. A second kind of cost information needed is a breakout of the discipline costs for civil, structural, mechanical, piping, electrical and process control, indirect costs, which sum to give the total installed costs. Indirect costs which cover owners costs, engineering and contingency. This provides the all-important balance-of-plant cost information, as the ratios are less subject to change with escalation over the years.

An older report provides such a breakout for rotary, cascade, flash, and indirect type dryers for four sizes of rotary dryers (MacCallum, 1981). As well, the costs were developed for two cases: a new boiler / dryer installation and a retrofit of a dryer to an existing boiler. One significant result of the analysis is that the total installed cost for the complete dryer system are very similar, if the wood fuel handling and storage is excluded for both cases. Though the costs are in 1981 Canadian dollars, the effect of escalation is compensated for by the exchange rate difference such that today's costs in US dollars are approximately equal to the amounts shown in the report.

This cost information is summarised in table 4 - 8. It should be emphasised that the material handling equipment such as conveyors, feeders and bins is not included in any of the cost information presented. These costs and retrofits where space is limited can add very substantially to the total cost of an installation.

Table 4-8
Capital Cost of Flue Gas Dryers (a) - Order of Magnitude

Type	Moisture Content In, % - Out, %	Equipment Cost Range k$/ODt/h	Total Installed Cost (b) k$/ODt/h
Rotary	55 - 40	80 - 45	370 - 160
Cascade	55 - 40	70 - 45	360 - 200
Flash	55 - 15	180 - 70	860 - 330

Notes: a - based on all the boiler flue gas entering at 300°C and leaving the dryer at 105°C.
b - the first value being for about 4 t/h, the second about 35 t/h.

During the course of this study, technical articles providing capital costs for three cascade dryer installations were identified:

- Cascades Inc., East Angus, Quebec cost 36M$Cdn in 1992, or the equivalent of 32M$US at the end 1995. Included both cascade and flash drying and suspension firing of part of the fuel (Pulp and Paper, 1993). The cascade dryer with a throughput of about 9.0BDt/h accounted for about 5M$US;
- Fletcher Challenge, Crofton, BC, cost 8.5M$Cdn in 1986, or the equivalent of 7.2M$US at the end 1995. The cascade dryer had a throughput of about 36BDt/h (Linderoth, 1986).

- Alabama River Pulp, Claiborne, AL, cost 6.3M$US in 1992, or the equivalent of 6.6M$US at the end 1995. The cascade dryer had a throughput of about 32BDt/h (Papermaker, 1993).

Another technical article describes a two line Flakt flash dryer installation at the Assi Lövholmen Linerboard mill in Pitea, Sweden (Westerberg, 1981). One unit supplies a lime kiln, the other, a recovery boiler converted to a power boiler. The units cost 17.5 M$US in 1980, or the equivalent of 24.5M$US at the end 1995 for both the 6 and a 13 ODt/h capacity, or about 9.5 and 15MUS$ respectively. A second article describes a Flakt flash dryer installation at E. B. Eddy Ltd, in Espanola, Ontario, which cost 14MCdn$ in 1986 and handles about 18 ODt/h of wood waste (Robinson, 1986). However, no cost data for actual mill-specific rotary dryer installations was identified in the literature during the course of the study.

A plot of all the data is presented in Figure 4 - 3 that follows.

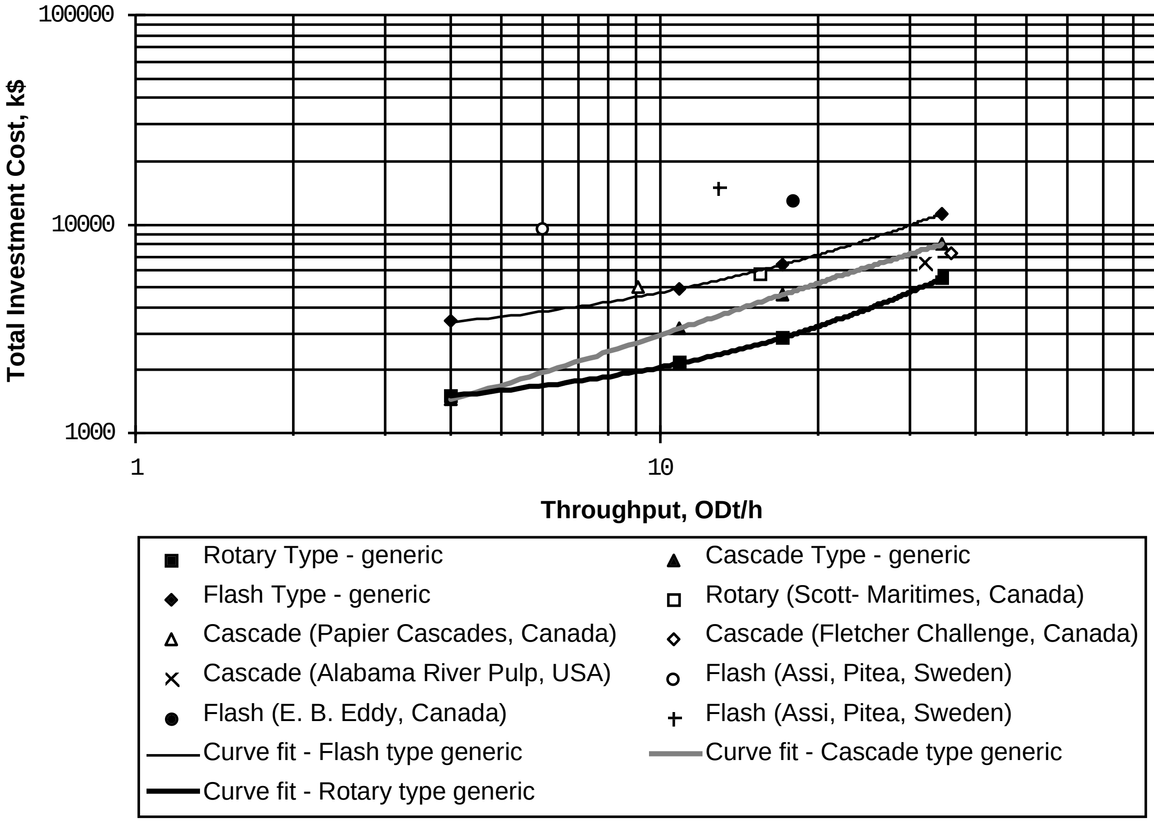


Figure 4-3 Total Installed Cost of Flue Gas Dryers

Operating Costs

The main components to the operating costs are cost of power and maintenance.

Power consumption based on oven dry throughput are: 8 - 14 kWh/ODt for rotary dryers; 15 - 20 kWh/ODt for cascade; 16 - 38 kWh/ODt for flash dryers, the latter depending on the size reduction required which is a large consumer of power (H. A. Simons, 1983; MacCallum, 1981). Size reduction power is highly variable depending on the equipment used, size distribution of the feed, product size, type of material being pulverised, species, initial moisture content. Summary data presented in a reference indicates a range from 10 to 100 kWh/ODt or more (Blackwell, 1984).

In the absence of data encountered in the literature on the maintenance costs of equipment, an allowance of 2% of total installed cost of the drying system equipment is suggested as the basis for preliminary evaluation purposes.

Environmental Aspects

This section deals with the composition, and factors affecting rates of emission from the flue gas drying process itself and control technologies; a later section describes the discharges from steam drying. The effect on combustion products leaving the boiler due to the firing of drier fuel has been summarised in Section 3 - The Effects and Benefits of Thermal Drying.

During flue gas drying of wet fuels, not only is water evaporated and particulate matter entrained by the flue gas, but also many different kinds of organic compound groups are volatilized as well. Some of these contaminants are removed in part by the emission control system before release to the atmosphere, others will pass through undiminished to the stack and atmosphere. As well, contaminant loads of particulate matter and volatile organic compounds in the entering boiler flue gas are modified after passage through the dryer, while many of the common emissions such as CO, NO_x, and SO_2 are not affected.

Particulate Matter

Evidence from the literature, most of it now 10 - 15 years old, describing operating boiler systems with rotary type flue gas dryers indicates that total particulate matter (PM) leaving the dryer is lower than entering, resulting in reduced stack emissions. In some cases the reductions are significant, as high as 50 - 80% (Johnson, 1975; Sanderson, 1980). The coarse fraction of the particulate matter in the flue gas stream is apparently reduced by the scrubbing action of the wetter fuel particles, while the very fine particulate emissions may generally increase if the fuel being dried contains a high proportion of fines. The mechanism for such reductions is by impaction of finer material on coarse wet fuel particles, but it is clear that reduction is not always the case, particularly if the wet fuel is composed principally of fine material and the stack emission limit is stringent. To any particulate passing though is added the condensable volatiles or aerosols, if the drying temperature is high enough to drive significant amounts off. Aerosol is the term used to describe solid or liquid particles of very small size that remain aloft for long periods and would typically be below one micron in diameter and are classified as PM even if in liquid form.

These condensable volatiles are not removed by mechanical dust collectors or dry type electrostatic precipitators and appear in the stack emissions and result in undesirable blue haze. As they are technically PM, they are mentioned, here but their generation and control are described under volatile organic compounds in the next section.

At first sight, it seems reasonable to expect that the retrofit of a flue gas dryer would not result in the need to upgrade an emission control system, as the particulate loading into the control device might be expected to diminish. However, the reduction in actual flue gas volume with flue gas drying will affect the emission control device in different ways. The lower velocities will reduce collection efficiency in the case of mechanical collectors; their performance will further suffer from the shift to a greater proportion of fine material and aerosols if the drying temperature is elevated. However, the lower velocities will increase the collection efficiency in the case of electrostatic precipitators since treatment time will increase, and percent moisture will be unchanged.

Equipment suppliers should be consulted for definitive answers specific to the case being considered.

Volatile Organic Compounds

There is very little information available specifically on dryer emissions from fuel drying in flue gas dryers. One survey reports other sources that give estimates of organics from wood residue fuels of 770 - 3450 mg as CH_4/ODkg (Fagernäs, 1996), and other data indicating terpenes in the 1500 - 7000 mg/ODkg range, total organic carbon as in 1000 - 2400 mg/ODkg range, aldehydes as in the 500 - 1300 mg/ODkg range. This same reference also presents results of tests on a cascade type and a rotary type flue gas dryer that indicates that the cascade type has considerably lower organic emissions, though the alcohol and acid components of VOC were not analysed.

Other work in the last decade on the volatiles generated from steam drying of wood and wood residues in processes used in the wood products industry is relevant, however. The air emission potential of kiln drying of lumber, particle / fibre drying and veneer drying in the panelboard industry, and even mechanical pulping since, at the grinding zone, the wood temperature is estimated to be 100 - 200°C (Mackie, 1995). From 1990 to 1995, a coordinated and extensive program of test work in the US reported by NCASI was undertaken to gather data on emissions from process units in the wood products industry to assist the permitting process. Emission data specific to dryers is presented for particleboard, medium density fibreboard, oriented strandboard, and plywood mills (NCASI #657, 1994; NCASI #693, 1995; NCASI #694, 1995; NCASI #695, 1995). The large number of data reflecting differences due to species, particle size distribution, heating process and other factors and make it inappropriate to include data here. However, no data on air emission testing of wood fuel dryers has been published by NCASI (Jain, 1996)

Though both flue gas and steam drying processes use relatively low temperatures of 100 - 400°C, the thermal treatment brings about changes in the organic material, even under the more mild of these conditions. As they contain a larger proportion of volatiles, the release of these components is greater for wood, bark and wood derived residues than for than peat, lignite or bagasse. The organic compounds released may also cause operational problems downstream by contributing to the formation of deposits if conditions favour condensation on duct and other surfaces.

In the case of wood and wood residue drying, the groups of compounds of most significance to air emissions are the volatile monoterpenes, other condensable lipid compounds and products of thermal degradation. For air emission and control perspective, a distinction is made between those that remain volatile at ambient conditions and those that condense. These aspects are reviewed in a recent report for the International Energy Agency (Mackie, 1995), from which the following is a summary; the reader is referred to the original source for further details.

Volatiles The most volatile emissions consist of monoterpenes. Monoterpenes are naturally emitted from wood and the emission rate increases when the surface area or the temperature of the wood are increased. Monoterpenes have boiling points of 150 - 190°C. The major components are α-pinene and β-pinene. Monoterpenes are strong smelling irritants. Photochemical reactions of monoterpenes with ozone produce aerosols which form a visible haze similar to the natural haze found over forested areas. There is environmental concern over natural and other emissions of monoterpenes because of photochemical reactions of monoterpenes with nitrogen oxides to form low level ozone. Ozone is a strong oxidant and a component of smog. In high concentrations, ozone is responsible for impaired lung function in human populations, crop damage and is believed to be responsible for forest damage in Europe and North America.

Condensables The condensible category of VOCs consists of other lipid compounds such fatty and resin acids, diterpenes and triterpenes. At common dryer temperatures of 180 - 220°C, these compounds have significant vapour pressures sufficient to be released, though their boiling points are much higher. Fatty and resin acids have boiling points of > 300°C. After release to atmosphere, these compounds condense to form either submicron aerosols in a liquid state or attach themselves to the surface of particles. The tacky fatty and resin acids are also presumed to contribute to the formation of deposits found on surfaces of bark and peat dryers.

Thermal degradation products The products of thermal degradation of wood include acetic and formic acids, alcohols, aldehydes, furfurals, and carbon dioxide, and are released starting at above 100°C, but become significant at higher drying temperatures, particularly above 200°C. Degradation product generation increases linearly with temperature and is greater in the presence of air because of oxidation products. The more intense the drying, shorter retention times, higher temperatures and lower final average moisture content results in higher acetic and formic acid concentrations. Malodorous emissions may be caused by the carboxylic acids and the aldehydes. Formaldehyde is a strong smelling irritant, a suspected carcinogen and identified by the EPA as a hazardous air pollutant; this emission increases with drying intensity. However the main preoccupation of emission control, up until 1990 or so, has been to reduce the visibility and odour of stacks and vents from these wood processing industry sources and mechanical pulp mills.

Some degree of control of VOC emissions in the process from flue gas drying is achieved by lowering peak temperatures, recycling of part of the flue gas leaving the dryer back to the inlet, and reducing the quantity of fine material in the dryer feed material and its residence time.

At present the most effective add on controls for fine PM and aerosols are wet electrostatic precipitators which diminish the risk of fires of the dry type, and the less common moving media filter bed or electro-filter bed scrubbers. Where air emission control involves the use of a scrubbing water fluid such as wet scrubbing or wet electrostatic precipitator, condensation of part occurs and the purge stream will contain the less volatile water soluble compounds requiring suitable treatment before release to the watercourse.

Further control is possible in principle by the use of regenerative thermal oxidation systems, but the necessity of using fossil fuel runs counter to the purpose of the flue gas drying. Return of wet dryer gases to incineration points such as large boilers presents similar disadvantages because of loss of boiler efficiency through higher stack losses. Biofiltration, a recently developed process which uses bacteria on a substrate to biodegrade the contaminants in the gas stream, avoids the use of fossil fuel, and presents a significant advantage for that technology.

Steam Dryer

Types

Using steam to dry moist fuels has attracted recent interest, because of the advantages of the low risk of fires, high energy efficiency, and better environmental control. Another driver of its rapid development has been the increasing intensity of research, particularly in Europe, on the gasification of renewable fuels, or biomass, because the introduction of significant moisture with the fuel carries a heavy efficiency loss penalty in the gasification process.

The main components of a steam dryer are the fuel feeder, the flash dryer ducts or fluid bed depending on the concept, the fines classifier / cyclones, the blower for recirculating the steam, and a heat exchanger to reheat the superheated steam. The recirculating steam can be near atmospheric pressure or at a higher pressure; in either case the steam is in a superheated condition to provide the thermal driving force necessary to evaporate the moisture in the fuel. The source of heat can be either very hot gases, or high pressure steam.

The excess steam generated, equal to the amount of moisture driven off, is at a lower energy level than the heat supplied, though still superheated to avoid condensation. This fuel moisture-derived steam contains contaminants volatilized from the wet fuel. The virtual absence of flue gas, air, or other non condensible gases means that the latent heat of vaporization of the fuel moisture evaporated can potentially occur at a single temperature governed by the dryer pressure.

This better thermal efficiency of the steam dryer when compared to the flue gas dryer is only realised if the latent heat of vaporisation of the contaminated steam is returned usefully to the thermodynamic cycle. Though this heat is not available at a very high temperature, potential uses for the heat are in the heating of feedwater and returned condensate. The resulting condensate contains organics, however, and requires appropriate treatment.

In the 1980s, an energy efficient steam drying technique using superheated steam or turbine backpressure steam was developed in Sweden by Modo-Chemetics for drying wood pulp, bark, agricultural products, peat and other biomass materials under pressure. Since that time, different forms of steam dryers have been developed, tested and in some cases, commercialised.

This study has identified a myriad of different approaches to steam drying. Steam drying technologies may be atmospheric or pressurised, have short to long residence time, be large or small, and take very different forms physically. As well heat sources may be steam, flue gas, or a heat pump. Some of these process aspects are compared in the Table that follows.

Table 4-9
Steam Dryer Types

Company	Name of System	Evaporative Capacity Range, t/h	Operating Pressure in Dryer, kPag	Steam Pressure of Heat Source, kPag	Average Residence Time, Order of Magnitude, s
IVO	High Pressure Steam Dryer	(a)	300 - 2 200 (a)	-	2 - 3
IVO	Bed Mixing Dryer	(b)	≈0	-	2 - 3
Lurgi	SFBD, Steam Fluidised Bed Dryer	>150	15 - 25	400 - 900	-
Niro	Superheated Steam Fluid Bed Dryer	1 - 40	200 - 300	1500 - 2800	300
Stork	Exergy Steam Dryer	0.3 - 63	50 - 550	1000 - 2000	10 - 100

NOTES:
a - One 0.7 ODt/h pilot plant, and range of pressures tested
b - One demonstration plant of 5.6 Odt/h
c - several developmental prototypes.

This study has identified a number of companies developing steam drying. Stork Friesland Scandinavia of Sweden and Niro of Denmark, have multiple commercial installations in the drying sludges and pulps in the agricultural industry, wood residues and peat. IVO of Finland, has a pilot plant of its High Pressure dryer.

In addition, steam dryers have been recently developed by two companies for drying lignite or low rank coal, peat and wood residues. The Lurgi technology from Germany uses a bed of the material being dried as the heat transfer medium. And IVO has a second technology which uses the recirculation of hot sand bed material from the fluid bed furnace to meet the heat needs of the dryer.

A steam drying system developed by Modo-Chemetics for wood waste fuels was adapted from earlier work on pulp drying and was promoted in the early 1980s for fuel drying. Only one such system was installed, and is no longer in service. This technology, similar to Stork's, is no longer being offered and is not considered further.

Simplified block diagrams of the types are presented in Fig 4 - 4 that follows.

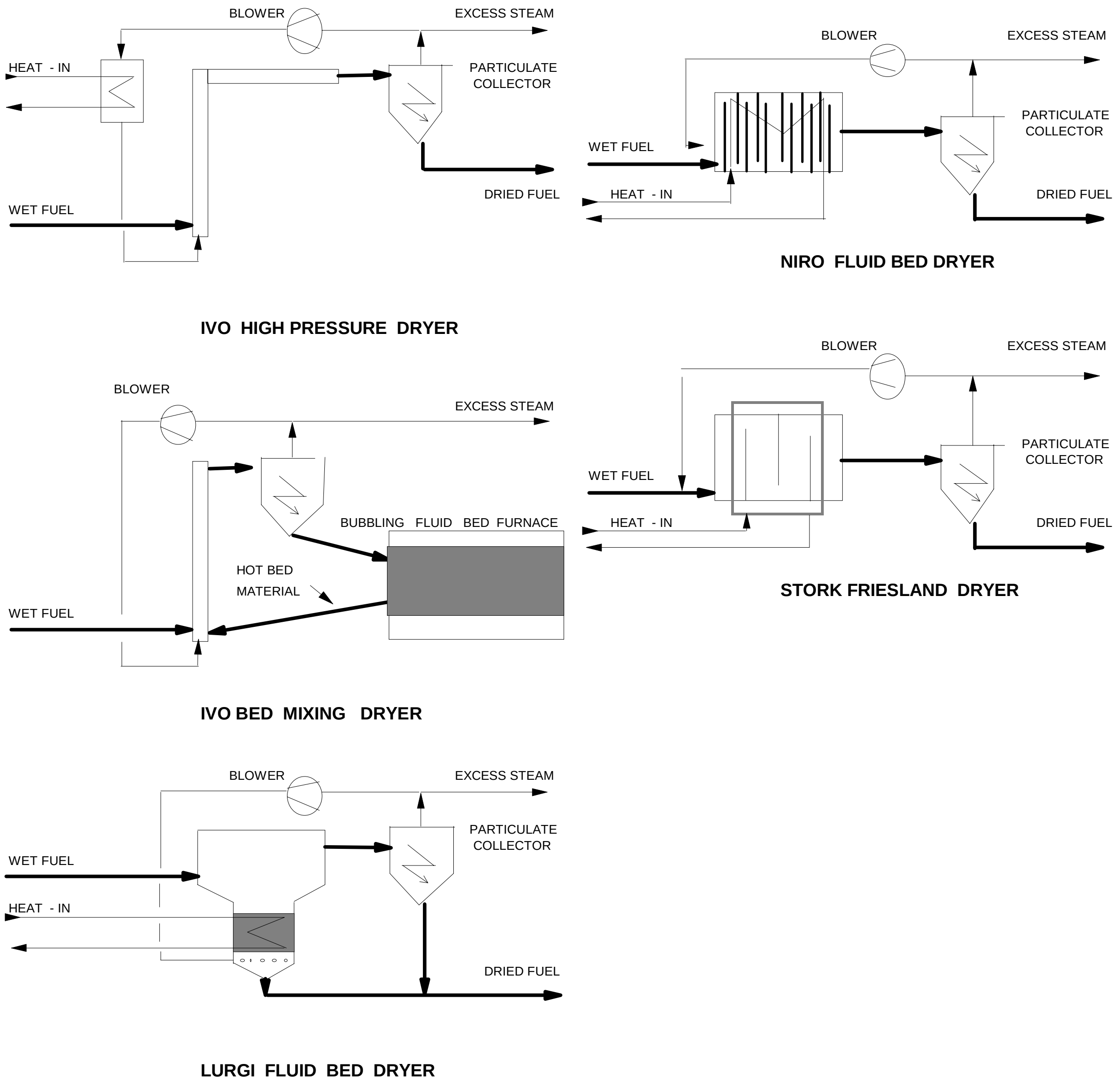


Figure 4-4 Types Of Steam Dryers

Manufacturers

IVO

Imatran Voima Oy (IVO) of Finland, the engineering arm of the Finnish national utility, has developed two types of steam dryers.

The first is its High Pressure Steam Dryer. A small 1t/h pilot plant was built in 1991 operating at pressures up to 2200kPa and temperatures up to 370°C. It is one part of their development of the IVOSTDIG cycle, an advanced gasification power plant for biomass fuels comprising the pressurized steam dryer, a pressurized air-blown gasifier, and a gas turbine where the excess dryer steam is used to augment the mass flow of the gas turbine. Since 1991, the dryer alone has been tested on peat, wood chips and papermill sludge. IVO has also conducted studies where the High Pressure Dryer us used at separate applications at pressures ranging from 300 to 1700 kPa on pulp and papermill sludges and up to 2200 kPa on some other biofuels.

The second technology which was developed later is IVO’s Bed Mixing Dryer. This is suitable for combustors utilizing fluid bed combustion, and preferably where the low temperature heat can be put to good use, such as in condensing type power generation or cogeneration plants where low temperature can be used. The unit operates at atmospheric pressure. The essential difference with the other steam dryers is that the drying steam is reheated by hot bed material extracted from the boiler's bubbling fluidized bed combustor. Wet fuel is added to a high speed stream of superheated steam and hot bed material and is pneumatically conveyed along until suitably dry. The dried fuel and bed material are then separated from the dryer steam in a cyclone, and fed directly into the fluidised bed combustor. Some of the dryer steam is recycled back from the cyclone to the lower part of the dryer tube, and the balance is bled off, which allows the latent heat to be recovered near atmospheric pressure.

The first application of the Bed Mixing Dryer was to the wood and peat fired power and district heating plant at Kuusamo, in northern Finland, commissioned in 1994. The plant has a generation capacity of 6MW and a district heating output of 17.5 $Mw_{thermal}$ without the dryer and 21.2 $Mw_{thermal}$ with the dryer operating and uses the same amount of fuel in both cases. An overall thermal efficiency improvement of 10 - 15% has resulted with the new dryer.

Lurgi

The Lurgi technology from Germany uses a fluidised bed consisting itself of the material being dried. The material to be dried must be capable of assuming and maintaining a granular form, but many materials according to Lurgi, exhibit this property, including: peat, lignite, sewage sludge, pulp and paper mill sludge, agricultural byproducts, ore and mineral sediments.

Heating of the wet material and reheating the superheated steam is by a heat exchanger tube bundle which is immersed in the bed material and provides very high rates of heat transfer. The heat source would normally be fresh high pressure steam. The dust collector for a Lurgi system would be an electrostatic precipitator.

Lurgi also has an alternate design, the WTA: Fluidized Bed Drying with Integral Waste Heat Recovery, using mechanical vapor recompression, a form of open cycle heat pump which compresses the moisture vapor driven off the fuel which then becomes the heat source.

The original concept, developed at Monash University, Australia and at Kombinat Braunkohlen-Kraftwerke Peiz (today VEAG, the German utility) in former East Germany, was first installed at commercial scale in 1986 at Brona, near Leipzig, Germany. Anther plant of 24t/h evaporation started up in 1993 at Traralong, in Victoria State, Australia drying run-of-the-mine brown coal at 63% moisture. Other potential applications are envisaged in the area of coal, sewage sludge, ore/mineral slurries, agricultural byproducts and wood refuse.

Lurgi are currently commercialising this technology for application to brown coal, lignite, peat. At 150T/h or above evaporative capacities, sizes are much larger than any of the other types of dryers reviewed.

Niro

Niro of Denmark has commercialised its Superheated Steam Fluid Bed Dryers and have numerous installations. The fluid bed operates under pressure of 200 - 300kPag (29 - 44 psig) by circulating steam in a closed vessel. Wet material is fed into the first of 16 vertical cells arranged around a centrally located heat exchanger. In the cell, the material is kept in suspension by superheated steam entering from the bottom. The material moves successively through each of the 16 cells and is finally discharged by a screw conveyor.

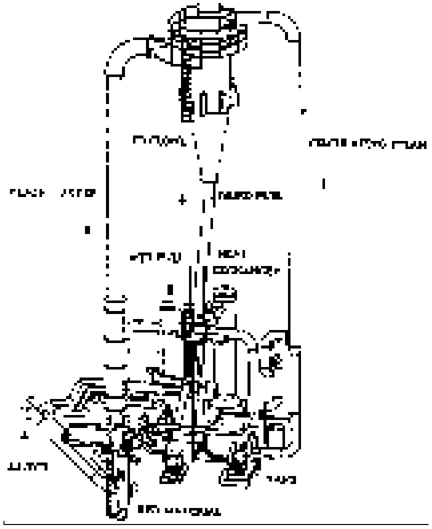
Niro installations are mainly applied to the drying of sludges and other byproduct materials in the agricultural industry as a part of reprocessing.

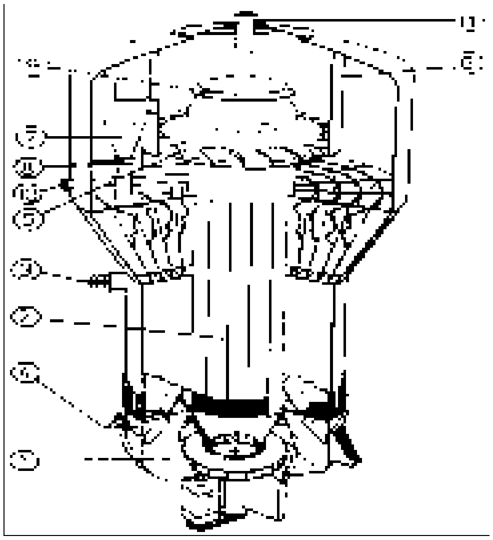
Stork

Stork Friesland Scandinavia AB of Göteborg, Sweden, has commercialised its pneumatic conveying tube type dryer and have numerous installations.

The wet solids are fed into a stream of superheated transport steam at 500 - 5500kPag (7 - 80 psig) by a pressure tight feeder. The mixture flows inside a succession of vertical co-axial tubes heated externally by steam, either high pressure steam from a boiler or steam extracted from a steam turbine generator, hot oil or other source. Sufficient of these co-axial heat exchanger tubes are provided to ensure the desired dryness is achieved by the pneumatic conveying of the wet material within the inner tube. The dried fuel is separated from the steam in a cyclone, from where it is discharged. Part of the steam is recirculated by a centrifugal fan to the inlet of the first co-axial heat exchanger tube, the balance being withdrawn for further use in the process or for reboiling to produce clean steam.

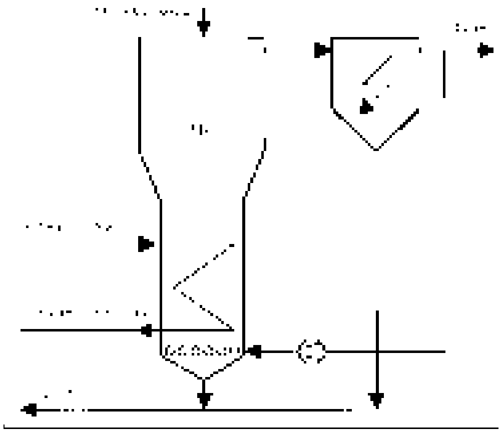
Supplier equipment schematics taken from the sales literature or technical brochures of IVO, Lurgi, Niro and Stork are presented in Figure 4 - 5 that follows.

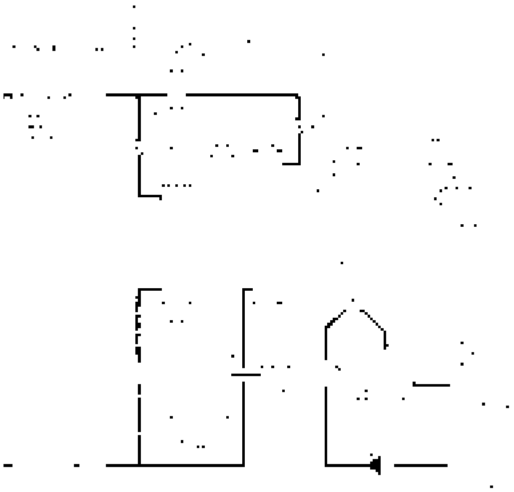




IVO - Bed Mixing Dryer

Niro - Superheated Steam Fluid Bed Dryer





Lurgi - Steam Fluid Bed Dryer

Stork - Exergy Steam Dryer

Figure 4-5 Supplier Concept Schematics

Applications

The steam dryer is a technology which has recently received much innovative effort, but is still relatively immature and total installations remain few.

The technology is to be found in a wide diversity of plants as Table 4 - 10 indicates.

Table 4-10
Distribution of Types of Steam Dryer Installations

	IVO	Lurgi	Stork	Niro
Agricultural Applications				
Sugar beet pulp	-	-	2	8
Other	-	-	5	-
Wood-related Applications				
Market pulp	-	-	2	-
Wood chips, sawdust	1	-	-	1
Bark	1	-	1	1
Other Applications				
Peat	-	-	2	-
Lignite	-	2	2	-
Municipal Waste Water Treatment	-	-	1	-
Sludges	-	-		
Other				
Total number installed:	1	2	15	10

NOTE: a - as of spring 1996 about 14 installed and under construction (Jensen, 1996)

Drying Potential and Performance

Though steam drying is not limited by concerns of fires or low temperatures in flue gases causing corrosion, there are process constraints on such systems.

The use of excessively high temperatures in steam dryers will result in the volatilisation of part of the fuel, with the contaminant level in the resulting condensate being excessively high, and loss of fuel heat content.

The superheat of the recirculating drying steam is achieved by heat exchange with the heat source. From Lurgi's literature, the high pressure steam required for lignite and peat steam dryers is 400 - 900kPag, giving dryer steam temperatures of 120 - 150°C, assuming a 40°C ΔT. For agricultural and wood residues, the corresponding pressure is 1000 - 2500kPag giving dryer steam temperatures of 144 - 186°C, again assuming a 40°C ΔT.

The minimum temperature of the recirculating drying steam is a function of the operating pressure of the dryer. For efficient use of the dryer capacity, the steam must remain superheated. A ΔT of 20°C above saturation temperature is suggested, though equipment suppliers will have their own criteria.

The throughput rate, evaporation capacity and other design and performance data of a Niro system described in the literature (Jensen, 1994, 1996) are presented in Table 4 - 11.

Table 4-11
Representative Design and Performance Data for a Niro A/S Steam Dryer[(a)]

Evaporation		t/h	27.2
Capacity		ODt/h	10.8
Moisture content	feed	%	70.8
	discharge	%	10
Thermal requirements:			
	without heat recovery	GJ/t_{evap}	3.45
	with latent heat recovery	GJ/t_{evap}	0.40
Blower power		kWh/t_{evap}	67

Note: a - (Jensen, 1994).

Costs

Capital cost

Very preliminary order of magnitude of cost data supplied in literature from Lurgi dated 1994 are 0.8 - 0.9 million DM or 500 000 - 600 000$ per tonne of evaporation per hour. IVO High Pressure Steam Dryer system total installed costs are expected to be of the order of 300 000 - 400 000 $\$/t_{evap}/h$, which includes a pulveriser for some size reduction.

Operating Costs

The main components to the operating costs are cost of power and maintenance. Power consumption data is very limited, but literature from Lurgi, Niro and IVO suggest a range of 20 - 45 kWh/ODt throughput excluding pulveriser; the latter could add another 10 - 50 kWh/ODt.

In the absence of data encountered in the literature on the maintenance costs of equipment, an allowance of 2% of total installed cost of the drying system equipment is suggested as the basis for preliminary evaluation purposes.

Environmental Aspects

This section deals with the composition of contaminants in condensates that arise from the steam drying process itself and control technologies; an earlier section describes the air emissions from flue gas drying. The effect on the contaminants in the flue gas leaving the boiler itself due to the firing of drier fuel has been summarised in Section 3 - The Effects and Benefits of Thermal Drying.

In steam drying, contaminated condensates are formed when the water and other less volatile vapours evaporated from the wet fuel are condensed after drying and the energy is recovered. Waste waters are also formed when flue gas is scrubbed with water, or if drying is preceded by a dewatering step such as pressing, commonly used for wood bark and bagasse to reduce moisture to the ≈50% range.

The compound groups and factors affecting the evolution of contaminants from wet fuels such as wood, bark and peat has been discussed in the earlier section relating to flue gas dryers. The organic load or strength of the contaminants is found to be surprisingly high and increases rapidly with increasing drying temperature; one reported a tripling of BOD, COD and TOC loads from peat as temperatures were increased from 110°C to 130 - 140°C, while the same parameters doubled for forest residues as temperatures were increased from 140°C to 160°C. For peat the dry weight loss increased from 1% at 190°C to 10% at 350°C (Fagernäs, 1996).

Waste water data specific to steam dryers is presented in Table 4 - 12 based on the reference (Fagernäs, 1996).

Table 4-12
Wastewater Characteristics from Steam Dryers

	Wood and Bark	Peat
BOD, mg/L	800 - 1700	130 - 530
mg/ODkg	340 - 12 800	140 - 510
COD, mg/L	1900 - 2900	300 - 880
mg/ODkg	1100 - 1250	440 - 850
TOC, mg/L	480 - 9700	310 - 5000
mg/ODkg	9500 - 27 000	90 - 56 000
Solids, mg/L	5 - 390	80 - 350
mg/ODkg	390 - 1700	30 - 8000
pH	3.3 -5	3 - 6.8

Other work reported on the mild distillation of peat at 180 - 220°C for 30 minutes showed 12 - 14% of the dry weight of peat as dissolved solids in the condensates which had a COD of 14 000 mg/L (Mackie, 1995).

The condensates from drying processes of forest residues are found to be toxic; this is increased by higher proportions of bark and needles. For one proposed plant, twenty-fold dilution was proposed before discharge to the community wastewater treatment system (Fagernäs, 1996). Some tests by IVO on the condensates from the steam drying of peat indicate that those condensates are not toxic (Hulkkonen, 1996)

Other data indicates that for steam drying operating at 2300kPa / 220°C, the TOC of was found to be 1100 - 1500 mg/L for crushed wood chips and 450 - 900 mg/L for sawdust (Hulkkonen, 1994). Lipophilic compounds, which are potentially tacky at drying temperatures, were measured at 2300 - 4400 mg/L or 0.20 - 0.45% of the dry weight of which 70 - 90% were fatty and resin acids. The condensates from the pressurized drying experiments were found to contain lower amounts of lipophilic extractives than those from atmospheric drying experiments.

These condensates require treatment before release to the water course. Conventionally, this would comprise neutralization, decantation or filtration of suspended solids and biological treatment for reduction of oxygen demand and toxicity. Alternatively, steam stripping may be found efficient to concentrate the impurities. This would allow recovery of the energy in the organics rich stripper off gas stream for firing in the boiler.

The terpene rich non condensible portion of the dryer steam, which also contains CO_2, and lesser amounts of H_2, CO, CH_4, and C_2 - C_4 compounds (Fagernäs, 1996) is best disposed of by firing in the boiler or furnace receiving the dried fuel.

5

INTEGRATION OPPORTUNITIES

Some applications of dryers bring greater economic and operational benefits than others. The purpose of this section is to identify opportunities where the application of dryers is most beneficial.

The chapter commences with a short section that lists some of the factors and circumstances which favour fuel dryers. Subsequent sections present the results of investigations of specific integration cases considered.

Types of Systems with Potential for Drying

It is possible to comment on the factors that appear to provide the best opportunities for dryers and chances for their economic justification, based on the information furnished by dryer system suppliers and described in the literature, and as a result of reviewing a number of drying opportunities. These factors favouring dryers are:

- <u>Expensive fuels are displaced</u> The substitution of an expensive fuel, frequently but not always fossil fuel, with less expensive biomass fuel is more easily justified the wider the price spread. But it is also true that the higher the cost of a wet biomass fuel, the more easily the additional expense and complexity of a dryer system can be justified. The high cost of fossil fuel in the late 1970s - early 1980s resulted a great number of wood fuel firing improvement and numerous dryer projects in the pulp and paper industry.
- <u>Fossil fuel is used to improve boiler flexibility and control</u> If the use of fossil fuel is needed to sustain combustion of wet fuel on the grate, then external drying of the wet fuel may be sufficient to reduce or eliminate the need for sustaining fuel.

- <u>Existing Boiler and ancillary equipment limit the amount of wet fuel that can be combusted</u> If the ability of the boiler to burn grate fuel is limited due to the moisture in the fuel necessitating supplementary firing to meet steam demand, or the boiler tube erosion rates or fan capacities are the limitations to burning more wet fuel on the grate, then drying of wet fuel will be advantageous.

- <u>Elevated stack emissions present a permitting problem</u> If the particulate, volatile organic compound or other emissions are the limitations to burning more wet fuel most likely to be the case only on the grate, then the use of a dryer , by improving the combustion process will probably be advantageous.

- Low temperature heat is needed in the steam cycle A steam cycle which permits the recovery of the latent heat in the moisture evaporated from the fuel will result in further fuel being saved. This gain will be in addition to the improved combustion efficiency. In this case, a steam dryer which improves both the combustion efficiency and the steam cycle efficiency may be more easily justified economically than a flue gas dryer.

Similarly, there are other that factors that clearly work against the technical and economic justification of dryers:

- Wet fuel more than 52 -55% moisture wet basis For instance, in the case of wood residues and / or pulp and paper mill sludges, experience shows that mechanical pressing will probably be found to be the most energy efficient and cost effective than thermal drying. However, this does not mean that drying to lower levels than this level would not be justified on its own merits.

- Biomass or sludge fuel that is of very low, zero or of negative cost The investment costs associated with substitution of fossil fuel by a low or negative cost renewable fuel is more easily justified the larger the cost difference between the fuels. Such an investment might include fuel handling and firing equipment and a new or modified boiler This is true whether the investment includes a dryer or not. However, it does not follow that the additional or incremental investment associated with drying is easy to justify. In fact, in some situations it may be more difficult to justify fuel drying, the lower the cost of the renewable fuel, because the savings through improved fuel efficiency are correspondingly lowered. Consider a large or unlimited supply of sludge with a negative fuel cost (a disposal cost for landfilling), which favours low combustion efficiency. In such circumstances, drying almost certainly cannot be justified in new equipment, as the economics drive in the other direction, to decrease combustion efficiency. However, the benefits of reduced flue gas volume and easier operation remain, and affect costs. Also, in existing operations, if the supply of sludge is limited, or the existing boiler design has limitations or bottlenecks which are relieved by drier fuel, then the drying of wet disposal material may be justified.

- Retrofit situations where the stack temperature is already low In the case of an existing wet fuel boiler where the stack temperature is already low and cannot be lowered further because of the risk of corrosion of emission control equipment, ducting and stack, the addition of a dryer would require a separate dried fuel burner for a heat source, further adding to the investment and complexity of the system and making justification more difficult.

- Ash deposition or slagging problems Where the ash analysis indicates a high ratio of alkaline metal oxides to silica, the slagging and fouling tendencies of the boiler will be increased with the increased temperatures resulting from drying wet fuel. A flue gas type dryer may result in aggravated slagging because of the recycle back into the boiler of fly ash picked up in the dryer by the drying wet fuel.

- Absence of a biological treatment system Absence of means for the biological treatment of contaminated condensates from steam drying will favour flue gas dryer systems as opposed to steam dryers. If the plant uses wet scrubbers, whatever the drying system, treatment will be required of the scrubber effluents. The installation of a dedicated stand alone treatment system adds to the complexity and cost particularly if toxicity is to be removed. This contrasts with the addition of the contaminated condensates as a side stream of high strength waste to an existing system where the only significant effect is for oxygenation power; being a small flow, the effect on hydraulic retention time is negligible.

Cases Considered

The next sections describe the results of a preliminary evaluation of the application of drying technologies to three types of boilers all of which involve power generation. The first case considers the retrofit of wood cofiring in a large 300MW fossil fuel fired electrical utility generating station and the economic justification of flue gas or steam drying. The second case considers the retrofit of a steam dryer for a small 12MW wood residue only fired independent power producer. The third case treats the application of steam drying to the proposed retrofit of a fluidized boiler in a large kraft pulp mill where power is generated with a condensing steam turbine.

For each, the economics have been based on order of magnitude or factored estimates and are presented for preliminary comparative feasibility purposes only.

Utility Boiler Cofiring Case

This case considers the retrofit of a wood cofiring system to provide 10% of the steam generation for a 300 MW electrical utility generating station. The unit considered could in principal be designed for any one of three types of fuel: gas, oil or coal. This simplified analysis has been prepared to compare two cases: a dryer using flue gas and a dryer using steam.

Co-firing wood in an existing utility boiler has a number of predictable effects, but also introduces a number of uncertainties that could potentially affect operations negatively. These effects and uncertainties include:

- additional investment for wood drying and firing system;

- additional operating costs, particularly for electric power load associated with the fuel handling, drying and firing system and the increased fan power requirements of the existing fans due to the increase in flue gas mass flow, but also operating and maintenance personnel, maintenance materials;

- change in flue gas mass flow due to changed composition of the products of combustion and lowered peak furnace temperatures, both of which will affect the furnace exit gas temperature and radiative and convective heat transfer through the unit, and affect the stack temperature;
- decrease in boiler efficiency principally due to the greater amount of heat lost to the stack associated with the extra water and increased levels of excess air;
- in the case of steam drying only, changes to the steam cycle due to the return of low grade heat to the feedwater heating system;
- potential for heating surface deposits;
- potential for increased erosion rates of superheater, reheater and generating bank;
- changes or even increases in air emissions;

Some of these effects can be quantified at the pre-feasibility stage knowing the type of fuel. Others, such as heating surface deposits, increased erosion of generating bank and other tubes and changes in air emissions are clearly more problematic in the case of retrofitting co-firing with units designed for oil or gas fuel, than for coal fuel.

Thus the first case considered is that of wood co-firing in an existing coal fired unit. Heating surface deposits are unlikely to be a problem due to the higher silicate content of coal ash which will have a diluting effect on the impact of sulphates in lowering the ash melting points (Hupa, 1982). Erosion of generating bank and upper furnace tubes would be expected to change. On the one hand, there is less ash in most wood residues than coal. On the other, flue gas volumes are higher, increasing gas velocities and potential for erosion, though, probably not significantly. The unit would suffer slightly reduced electrostatic precipitator performance due to the reduced total sulphur input, but SO_2 emissions would be reduced by the adsorption of sulphur gases onto the wood fuel char. It has been assumed here that the electrostatic precipitator performance would not require remediation. Accordingly, it has been assumed for purposes of this preliminary assessment that the steam generator and steam turbine would not be derated for the retrofit of 10% wood co-firing.

Three options for wood co-firing have been considered: wood as received fired with coal, wood flash-dried and milled in a flue gas dryer for suspension firing; and wood dried in a steam dryer for suspension firing. The reason for including a wood firing as received Option is that drying as an additional wood fuel preparation step can then be isolated from the cost implications of the simplest Option: co-firing of wood in the as received condition. This is important as the cost of wood fuel selected is 17 $/ODT or 0.93 $/GJ which is very close to that of the 1.00 $/GJ price selected for coal. In practice, the wood firing as received case would only be practical in a coal fired unit equipped with a slagging-type furnace, where the wood could be added to the coal fuel. With a pulverized coal unit, without installing a grate, the wood fuel would have to be suspension fired which is not practical because of the high power requirements of milling green wood and the poor burnout of firing the wet wood.

The following sections describe the remaining impacts of co-firing that directly determine the economics.

Description of System

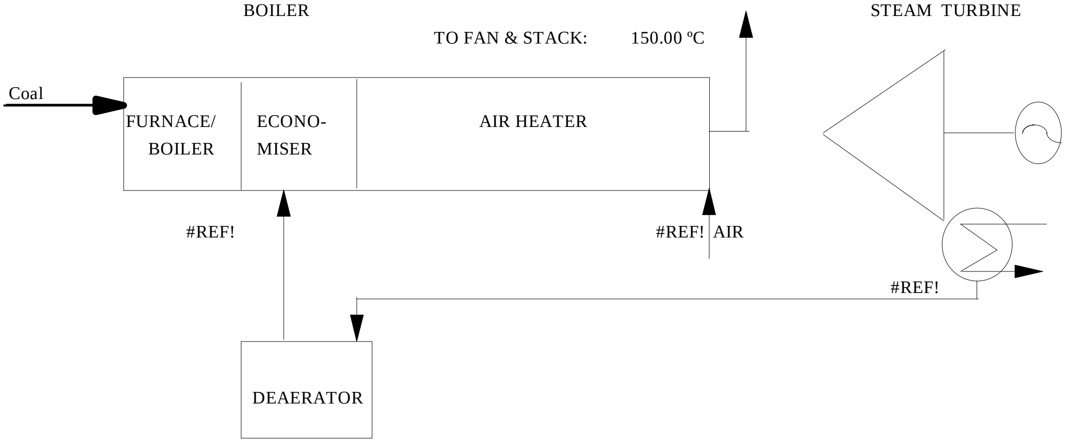
The flue gas flash drying system for wood co-firing comprises facilities for storing, stack out, reclaim, drying, pulverizing and firing systems for the wood in parallel to those for coal fuel.

The storage area includes an hydraulic truck dumper and provides storage for three days consumption of 55% moisture content wood refuse. The shaping of the pile and feeding of the reclaimer is performed by a front end loader. Reclaimed fuel is then transported by conveyor to a metering bin which feeds the flash dryer. A magnetic separator and scalping screen removes any metal or foreign or oversize material prevents it from entering the dryer and mill. In the case of firing wood as received, the wood is then added to the coal being conveyed to the boiler house.

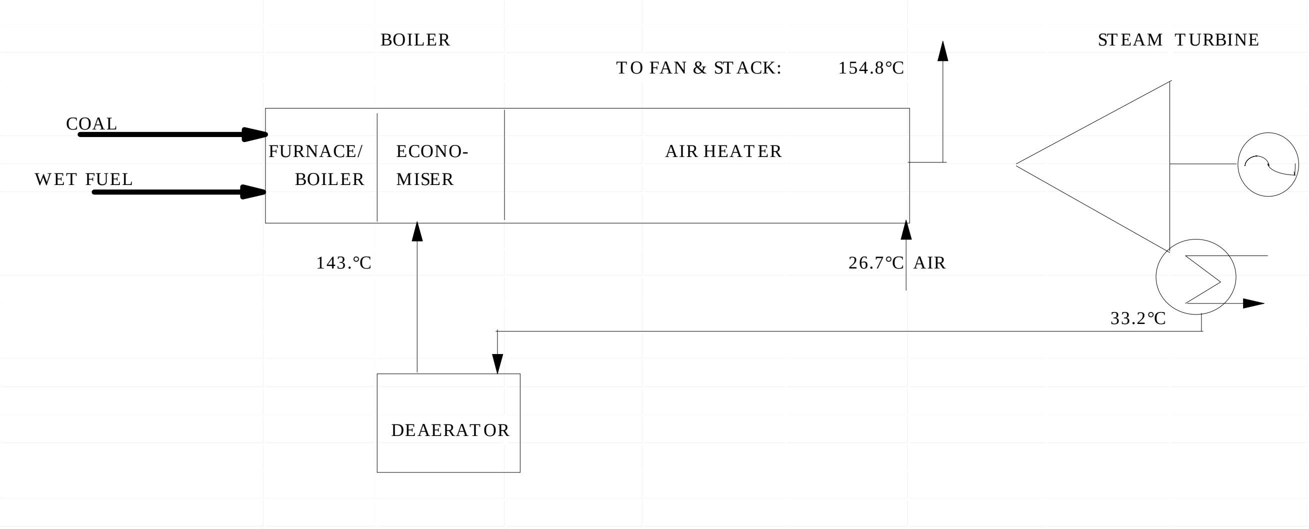
For the option of a flue gas flash dryer, the dryer built by ABB Flakt has been selected. This system is described elsewhere in this report. It comprises pre-dryer, pulverizer, and a flash dryer tube and would probably be built in a single line as an 18 ODt/h unit is in operation at E. B. Eddy, a paper company in Espanola, Ontario. The equipment would be designed for wet fuel feed at 55% moisture and a dryer outlet moisture of 15%. Cyclones would classify the fuel and return the oversize to the pulveriser. The dried fuel would be conveyed by primary air to new suspension burners by combustion air.

For the steam dryer Option, the IVO High Pressure Steam Dryer system has been selected and would use flue gas as a heat source. The dryer has been described in Section 4 of this report. The flue gas heat exchanger is proposed for pre-feasibility analysis purposes only, but is supported by limited tests; technical and operational feasibility remains to be demonstrated in practice. The additional surface would receive part of the gas from the economizer and return it before the air heater. It is assumed that this system would comprise a pulveriser before the steam dryer to reduce the material size somewhat to facilitate the drying efficiency. Surplus contaminated steam from the dryer would be used to heat combustion air and condensate returning from the condenser. The dried fuel would be conveyed by primary air to new suspension burners by combustion air.

Simplified flow schematics for the coal only, wood with no dryer (co-firing wood as-received) and two dryer cases integrated with the boiler and steam cycle are presented in Figure 5 - 2 that follows.\

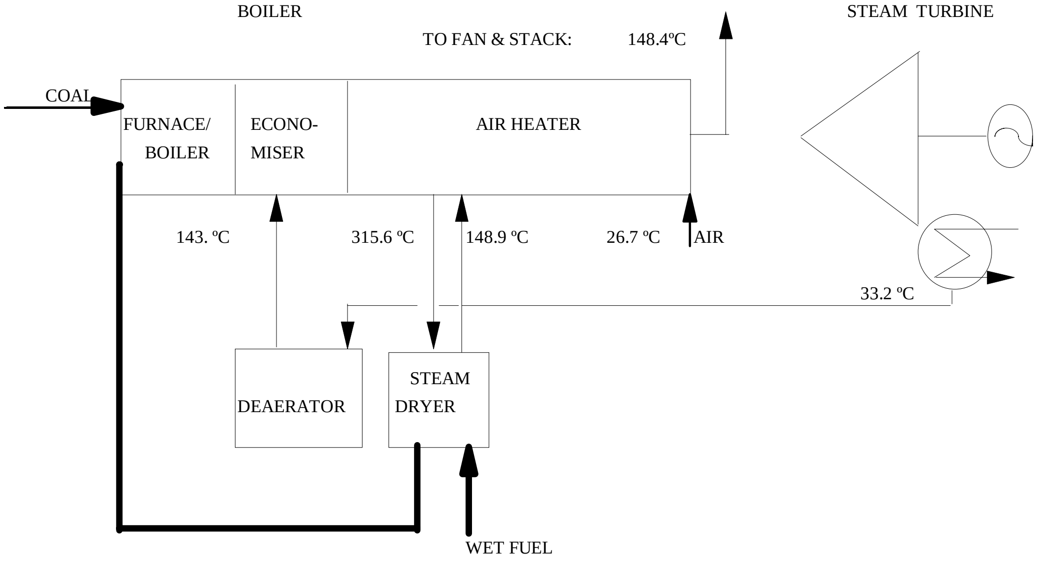


COAL ONLY

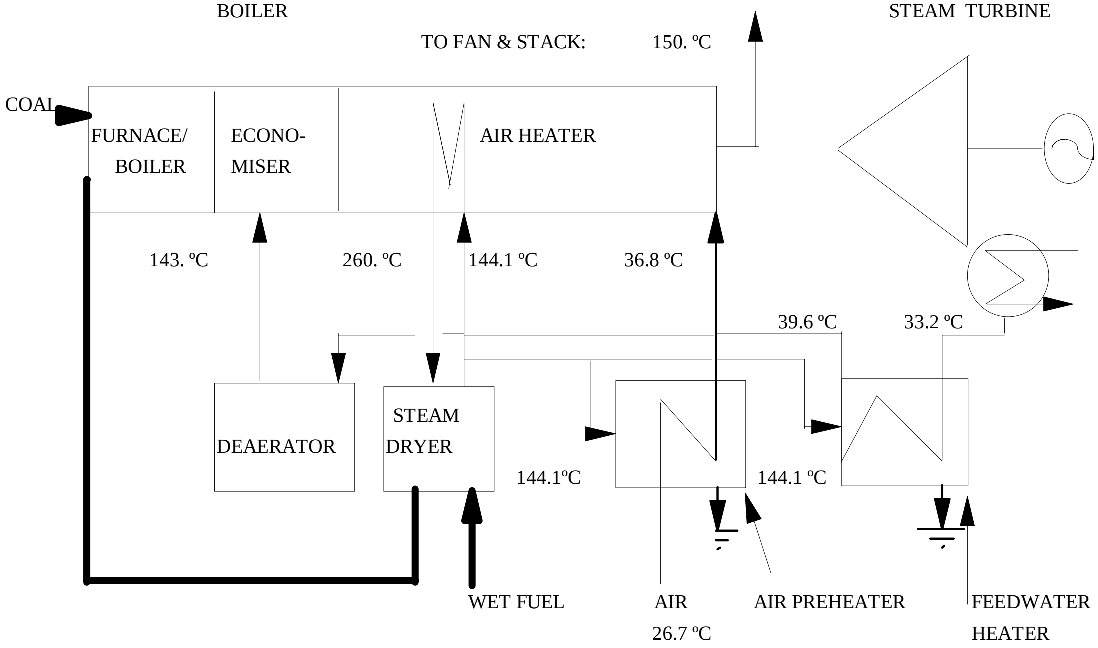


NO DRYER

Figure 5-1 Flow Schematics for the Utility Co-firing Case



FLUE GAS FLASH DRYER



STEAM DRYER

Figure 5 - 1: Flow Schematics for the Utility Co-firing Case (continued)

Changes to the Steam Cycle and Combustion

For the Wood As Received co-firing option, and the flue gas flash dryer and pulveriser option, there are no changes to the steam cycle, though the stack temperature is affected.

In the case of the Steam Drying option, the steam cycle is affected due to the recovery of a large portion of the latent and sensible heat of water evaporated from the fuel, but recovery of that heat is carried out in such a way so as to not affect the stack temperature. This is accomplished by the return

of the heat in the contaminated steam firstly to preheat air prior to the air heater, so that the heat removed from the flue gas after the economizer which causes the stack temperature to decrease is fully compensated for. The remaining heat in the contaminated steam is recovered as much as is practical to the feedwater heating system and directly displaces some of the steam otherwise supplied by the turbine bleed extraction.

The principle effects of changes to the steam cycle and combustion are presented in Table 5 - 1.

Table 5-1
Assumptions and Preliminary Estimated Changes to Combustion and Steam Cycle 300 MW Utility Co-firing Case

	Unit	Coal Only	No Drying - Wood As Received	Flue Gas Dryer	Steam Dryer
Wood Fuel Moisture Content, as fired	%	-	52	15	15
Stack temperature	°C	150	154.8	148.4	150
Excess Air[a]					
Coal	%	18	18	18	18
Wood	%	-	50	20	20
Boiler Efficiency	%	87.41	85.16	87.11	87.03
Turbine Heat Rate	GJ/kW	9906	9906	9906	9866

Notes: a - level assumed for boiler efficiency calculations

Power consumption and other Operating Costs

The parasitic power consumption of the plant will increase with wood co-firing. One source is the greater fan power requirements of the existing motor-driven fans as a result of handling larger flue gas volume flow. The second is the electric power load associated with the wood co-firing itself: fuel handling, drying and firing system depending on the option.

Allowances for power consumed are: 2.5MW for the wood handling and storage system, 3MW for the flue gas flash dryer and pulveriser and 0.8MW for the steam dryer. The power increase for forced draft and induced draft fan power is estimated from volume flow changes using total static head of 10 inches of water for each.

The source of this power is the generating station itself, so the result of all of the wood co-firing options is reduced station net generation. In this study we make the simplifying assumption that the cost of this power is available elsewhere in the utility system for the cost of the coal fuel used, namely 1$/GJ as fired, which is equivalent to about 12$/MWh. This is also a least cost assumption weighing in favour of wood co-firing.

There are additional operating costs associated with additional operating and maintenance personnel, maintenance materials, property taxes insurance, administration and overhead. For purposes of this study an annual allowance of 2% of total installed cost has been made in the economic evaluation.

Investment costs

The fuel storage, handling, flue gas flash drying and firing were developed to concept engineering stage and preliminary estimates prepared for appropriate for a pre-feasibility level of evaluation in a past study (Blackwell, 1984). The total installed costs for the flue gas flash drying system was estimated including indirect costs at 17MCdn$ in 1984. The updated cost using escalation factors to the end 1995 by and converting to US$ using 1.38 C$ = 1 US$ is 16M$.

The costs for steam drying are based on estimated supply and erect prices developed by IVO, with the balance of the installation being based on factored estimates which are considered appropriate for this preliminary screening type of economic analysis. This preliminary cost information is presented in the next table.

Table 5-2
Capital Cost of Wood Co-firing Options in k$ (Order of Magnitude)
300 MW Utility Co-firing Case

	No Drying	Flash Type Flue Gas Dryer	Steam Dryer (IVO High Pressure dryer)
Fuel Storage and Handling	4 880	4 880	4 880
Wood Fuel Drying and Firing	-	8 200	7 000
Modifications to the boiler	-	70	70
Subtotal	4 880	13 150	11 950
Indirect costs, including Owners Overhead, Engineering and Contingencies	1 120	2 850	2 650
Total Plant Capital	6 000	16 000	14 600

Economics and Return on Incremental Investment

The results of the estimated changes in fuel and power consumption on the return on investment for flue gas drying options considered is presented in Table 5 - 3.

Table 5-3
Incremental Operating Costs, Capital Costs and Return on Investment 300 MW Utility Co-firing Case

		Coal Only	**Wood As Received**	**Flue Gas Dryer**	**Steam Dryer**
Steam generation, gross	t/h	1059	1059	1059	1054
Power Generation	MW	300	300	300	300
Fuels Used:					
Coal	ODt/h	114.4	103.2	102.9	102.5
Wood	ODt/h	0	20.81	17.46	17.40
Operating Costs (partial):					
Coal 1.00$/GJ	k$/a	28 492	25 706	25 621	25 537
Wood 17.00$/ODT = 0.93$/GJ as received	k$/a	0	3 276	27 50	2 741
Power for complete wood system 12$/MWh	k$/a	Base	16.4	302	81
Other operating expenses 2% of TIC	k$/a	Base	120	320	320
Total of Operating Costs (partial)	k$/a	28 492	29 118	28 993	28 679
Operating Savings					
Savings over base	k$/a	Base	-626	-	-
Savings over As Received wood co-firing	k$/a	-	-	93.6	408
Capital Cost of wood co-firing	M$/a	-	6	16	14.7
Gross Payback on incremental investment of Drying Option over As Received wood co-firing	a	-	-9.5	107	25

The forgoing table of preliminary results shows that co-firing of Wood As Received is not justified economically over Coal Only firing. This is anticipated, given that the cost of wood residues is so nearly comparable to that of coal, 0.93 $/GJ vs 1.00 $/GJ and given the degradation in boiler efficiency. With the wood co-firing, boiler efficiency drops from 87.41% of the base case to 85.16%, a reduction of 2.25%. This efficiency loss is mainly due to the 4.8°C rise in stack temperature, from 150.0°C to 154.8°C, but flue gas mass is up as well. With this option, operating costs would expect to increase by 0.6M$/a, while at the same time requiring an investment of the order of 6M$. With the annual cost of wood of the order of 3.2M$, the sensitivity of the result to wood residue price is seen by inspection of Table 5 - 3: a 20% reduction in wood residue price would bring the option to operating cost equality with that of the Coal Only option.

The 10M$ incremental investment for the addition of a flash-type flue gas dryer to the wood co-firing case is not of much interest. The overall boiler efficiency improvement which reduces annual wood fuel costs by 1/6, about 94 000 $/a, saves a fuel that is relatively cheap and unable to justify this further investment. This, despite a boiler efficiency which has been increased to within 0.3% of the Coal Only option. The very low efficiency degradation is lower than would otherwise be expected when co-firing wood, but is because the stack temperature has been lowered significantly which offsets other losses. By removing heat from the flue gas entering the air heater, the flash-type flue gas dryer reduces the stack temperature. This has declined from 154.8°C for the wood-as-received option to 148.4°C, and is, in and of itself, an increase in boiler efficiency. For this option, the stack temperature drop may be considered an encroachment on the design basis of the original air heater, and credit that is not a legitimate one to support this option. For practical operating / maintenance reasons, as well, the stack temperature reduction may not be acceptable because of emission control equipment corrosion.

The use of steam drying technology, while not justifying the additional 8.6M$ over wood-as-received firing, improves the overall thermal efficiency further still. This efficiency improvement is, in part, due to the improvement of the steam cycle heat rate while retaining the stack temperature of 150.0°C of the Coal Only base case. This avoids improperly assigning efficiency credits to this drying option.

The sensitivity of the result to wood residue price is seen again by inspection of Table 5 - 3: for instance, a 50% reduction in wood residue price to 8.50 $/ODT would provide savings of nearly 1.8M$/a and a payback of 5.6 years for the incremental investment over the wood-as-received co-firing option.

Comments on Wood Residue Co-firing with a Gas Only or Oil Only Fired Utility

Co-firing wood residues in a utility generating plant designed for gas only or oil only fuel presents some problems already mentioned, such as potential for heating surface deposits, erosion of generating bank and other tubes and the need to provide for adequate particulate emission control. However, in the existing stock of plants in North America, it is not uncommon to find gas only or oil only fired units designed for another fuel, e.g.: pulverized coal. In such cases, therefore depending on the specifics of the particular design, erosion may not be a limitation.

It is however still useful to consider the economics of co-firing wood with natural gas or oil particularly as both fuels are at least double the cost of coal on an as received basis, providing a greater incentive to substitute cheaper fuel. For the case where gas fuel at 2.00$/GJ is fired, preliminary figures indicate that with wood at 17$/ODT (0.93$/GJ), more reasonable paybacks of the order of 4 years are possible. A 16M$ investment for the addition of a flash-type flue gas dryer is anticipated to result in fuel savings of 3.7M$/a, total operating cost savings of 3.4M$ and provide a 4.7 year payback for this co-firing option. A similar investment for steam drying is estimated to result in fuel savings of 4.0M$/a, total operating cost savings of 3.7M$ and provide a 4.4 year payback.

Particulate emissions will increase with wood firing. Consider the worst case where no precipitator has been installed as a provision for possible future coal firing. Even when firing the very cleanest wood waste such as off-specification chips with an ash content of 0.1%, the particulate concentration would be approximately 30mg/SDm^3 corrected to 6% O_2, assuming 50% unburned carbon in the fly ash. This level of stack particulate emission concentration is somewhat lower than current best practice emission levels in industrial wood fired plants in the US and stringent jurisdictions elsewhere. This might be acceptable to the authorities without the addition of particulate emission control equipment given the desirability of substituting renewable for non renewable fuels. However, such a clean source of fuel is unlikely to be available to a power plant on a continuous basis.

In the more likely case of firing bark and wood refuse containing 1% ash, assuming the same 50% unburned carbon in the fly ash, the particulate concentration would be of the order of 150mg/SDm^3 corrected to 6% O_2. With these emission levels there is no doubt that a relatively low efficiency electrostatic precipitator would be required. The total installation cost of an electrostatic precipitator sized for a 300MW gas fired unit treating all the flue gas to 20 mg/SDm^3 is of the order of 10M$ for the precipitator itself. Space restrictions caused by the layout or other problems could increase this amount significantly.

Small Wood Fired Independent Power Generation Case

Description

This case describes the application of steam drying to a small 12MW condensing power plant burning mill residues from area sawmills. The application is based loosely on an actual plant on the west coast, which is required to curtail power generation because of excessive moisture in the wood refuse fired in the winter. This is in spite of a cascade-type flue gas dryer that was part of the original design of the plant. The high moisture causes excessive gas velocities in the boiler gas passages and erosion of generating bank tubes. The case presents an opportunity to evaluate the advantages of steam drying which improve the steam cycle efficiency for the same stack gas temperature of 120°C. However, as many of the design data of the analysis have necessarily had to been assumed, and because of the preliminary nature of these case studies, the results are presented as if for a hypothetical plant. However, it is believed that the results reflect those that would be obtained with the actual design data of the plant in question.

The plant receives Douglas Fir and Redwood Bark by truck that has been size reduced at the wood processing mills. The bark has an average moisture of 55 - 59% in winter and 50 - 55% in summer. The fuel is screened and the oversize is passed through a hog. The bark is then dried in a cascade dryer located downstream of a tubular air heater and a mechanical collector. The dryer reduces the fuel moisture by approximately 5 percentage points.

The boiler is a bottom supported unit with a 4470 x 6100 mm (14' x 20') traveling grate generating steam at 6200kPag/440°C (900psig/825°F). Flue gas temperatures are: leaving the economizer, 290°C; leaving the tubular air heater, 190°C; leaving the cascade dryer, 120°C which is stack temperature. The flue gas particulate emissions are controlled by an electrostatic precipitator. The minimum stack temperature limit is to control corrosion in the electrostatic precipitator.

The steam turbine is rated at 11 735 kW with a throttle flow of 47 600kg/h, with zero extraction and a condenser pressure of 8.5 kPag (2.5"Hg). The deaerator steam is supplied by extraction steam at 190 kPa. The generator is designed for 13 800kVA corresponding to a turbine throttle flow of about 54 400 kg/h.

Changes to the Steam Cycle and Combustion

A base case is defined for a steam generation of 113.7t/h which results in the generation of 12MW. Greater steam and power generation beyond this results in excessive boiler tube erosion. This case establishes a limiting actual volume gas flow at the temperature at the entrance to the boiler generating bank. If the wood fuel were dried further in some way that did not lower the flue gas stack temperature, more power could be produced since the flue gas volume is the only factor preventing this in the existing plant.

A High Pressure steam dryer of the IVO type is selected for this option, using heat from flue gases. The dryer has been described in Section 4 of this report and is similar to the unit considered for the Utility Co-Firing Case. The flue gas heat exchanger is proposed for pre-feasibility analysis purposes only, but is supported by limited tests; technical and operational feasibility remains to be demonstrated in practice. The additional surface would receive part of the gas from the economizer and return it before the air heater.

It is sized for 23% of the wood fuel and reduces the moisture this fuel stream from the that leaving the cascade dryer down to 25%. The dried material then rejoins the balance of the fuel from the cascade and is conveyed to the metering bin and stokers for firing.

The addition of the steam dryer alters the temperatures in the boiler back passes as heat for steam drying is absorbed from the flue gases before the tubular air heater. This results in reduced heat available for the cascade dryer since the stack temperature must remain constant. Combustion air heating is therefore reduced somewhat, which incrementally reduces boiler efficiency. Compensating this, and tending to increase boiler efficiency incrementally, is the reduction of the flue gas temperature leaving the tubular air heater. The steam cycle is also affected as the heat recovered from the dryer steam, used to heat returning condensate, reduces extraction steam flow and increases power generation. These multiplicity of changes makes it difficult to anticipate the net result.

The IVO dryer is assumed to operate at 300 kPag (43 psig), and would dry 2560 ODkg/h of wood refuse from 55.3% to 25% moisture content wet basis, evaporating 850 kg/h water.

The principal effects of changes to the boiler and steam cycle based on the results of a preliminary analysis are presented in Table 5 - 4.

Table 5-4
Summary of Preliminary Estimated Changes to Combustion Process and Steam Cycle[(a)] Small Wood Fired Independent Power Generation Case

	Unit	Base Cascade Dryer	Steam Dryer IVO High Pressure Steam Type
Wood Fuel Moisture Content:			
as received	%	58	58
average, after cascade dryer	%	53	55.3
average, as fired	%	53	50.7
Temperature entering the Cascade Dryer	°C	220	200
Boiler Efficiency	%	63.9	66.4
Wood Refuse Fuel Used	ODkg/h	10 960	11 120
Power Generation	kW	12 000	12 860
Turbine Heat Rate	GJ/kW	11 637	11 440

Notes: a - assumes identical stack temperature at 121°C and identical actual wet volumetric flow rates entering the boiler generating bank at the same temperature.

Power consumption and other Operating Costs

The parasitic power consumption of the plant will increase with steam drying because of additional feeders, conveyors and the dryer steam blower recirculating the dryer steam through the flue gas heat exchanger and dried fuel and into the cyclone. There will be no significant power change for the forced and induced draft fans as the volumes are unchanged.

The allowance for the total additional power consumed is 150kW.

An annual allowance of 2% of total installed cost has been made in the economic evaluation to provide for additional operating and maintenance labor and maintenance materials, property taxes insurance, administration and overhead associated with the steam dryer.

Investment costs

The capital costs for steam drying have been based on preliminary estimated supply and erect prices developed by IVO, with the balance of the installation being based on factored estimates which are considered appropriate for this preliminary screening type of economic analysis. The preliminary order of magnitude capital cost is estimated at 2.5M$.

Economics and Return on Investment

The results of the estimated changes in fuel and power consumption on the return on investment for flue gas drying options considered is presented in Table 5 - 5.

Table 5-5
Capital Costs, Operating Costs and Return on Investment Small Wood Fired Independent Power Generation Case

	Unit	Base Cascade Dryer	with New Steam Dryer
Gross Steam Consumption	kg/h	51 560	54 320
Wood Refuse Fuel Fired	ODkg/h	10 960	11 115
Power Generated, Net Additional	kW	-	710
Capital Costs, Incremental, Steam Dryer	M$	-	2.5
Operating Costs (a) Wood Refuse 17$/ODT	$/a	1 726 200	1 750 000
Incremental Power 50$/MWh	$/a	-	298 200
Total Operating Savings	$/a	1 766 200	2 048 100
Total Operating Savings over Base	$/a	-	322 000
Payback, Gross, on Incremental Investment	a		7.8

Notes: a - Based on 8400h/a

With higher power buy back rates of 70$/MWh, the incremental savings increase to 440 000$/a and improve payback to 5.7 years. With lower power rates of 30$/MWh, the incremental savings decrease to 200 000$/a providing a gross payback of 12 years.

No allowance has been made for the better burnout of carbon with the addition of the steam dryer due to the higher combustion temperatures. Calculations were based on a loss of boiler efficiency of 4% due to unburned carbon which represents about 100 000$/a in fuel wasted. A 25% improvement in carbon loss would therefore increase annual savings with steam drying by 25 000 $/a.

Fluidised Bed Boiler Cogeneration Case

Description

This case considers the application of steam drying to the proposed retrofit of a bubbling fluidized bed furnace to an existing grate equipped boiler. The boiler is one of several meeting the steam needs of a large 1500 ADt/d kraft pulp mill. The proposed boiler modifications will allow the boiler to burn additional wood fuel to provide steam for a new condensing steam turbine. The addition of steam drying would improve the boiler and steam cycle efficiency, allow more steam generation from the boiler and more power generation than would be possible with undried fuel.

The boiler currently burns bark, wood residues from area sawmills and about 3% effluent treatment sludge. The bark, wood waste and sludge mixture has an average moisture of 50%. Wood refuse fuel is plentiful such that the proposed condensing plant size is not limited by the availability of wood residues. In fact, the cost of wood fuel is taken as zero, though it is likely to be available at a low price or the mill may even be able to charge a small disposal fee to wood residue producers.

This case is based loosely on proposals made for an actual kraft pulp mill in western Canada. As in the previous case, though, the results are preliminary and incomplete because of the preliminary nature of the concept analysis. These tentative results should therefore be taken as if for a hypothetical plant.

The boiler is a 1966 Foster Wheeler pin hole grate unit with steam generation at 4140kPag/400°C (590psig/688°F). Design steam generating capacity is 145t/h from wood in combination with 145t/h from oil/gas or 204t/h from gas/oil only. The lower furnace and grate will be replaced with a fluidized bubbling bed furnace which will burn 35 ODt/h at 50% moisture wet basis and generate 221.8t/h from the solid fuel mixture. The flue gas particulate emissions are controlled by a multiple cyclone. The stack temperature is 200°C at 100% MCR, 166°C at 70% MCR .

To study the effect of adding a steam dryer, a hypothetical single extraction condensing steam turbine is sized for the additional steam generated from the boiler once modified with the addition of a bubbling fluidized bed furnace only and one with a dryer. The condenser operating pressure is 10 kPag (3.0"Hg) as for the planned unit, but the extraction steam flow will meet the deaerator steam requirements for the whole condensing turbine portion of the mill steam cycle only. The hypothetical unit involves a number of simplifying assumptions appropriate for prefeasibility assessment ands serves to isolate the analysis from the rest of the mill. The planned future steam turbine will be a double extraction condensing unit of about 40MW, with a condensing section sized for flows that range from 50t/h to 110t/h, and average 63t/h.

Changes to the Steam Cycle and Combustion

A base case is defined for the new fluidised furnace firing as received wood waste generating 63t/h of steam which gives a power generation of 15.8MW assuming a turbine isentropic efficiency of 81%. Greater steam and greater resulting condensing power generation beyond this level is limited by flue gas velocities through the boiler generating bank and plan area heat release at the current fuel moisture levels.

An atmospheric steam dryer of the IVO type, a Bed Mixing dryer, is selected for evaluation and integrated into the system. As described in Section 4, hot bed material extracted from the fluid bed furnace is fed along with wet fuel into the vertical dryer tube containing superheated steam. After drying, the fuel and bed material are returned to the furnace via a cyclone, and the dryer steam is recirculated by a blower back to the drying tube. The steam dryer is sized to match the heat in the excess steam produced to the heat that can be absorbed by the condensate returning to the steam cycle from the condenser of the steam turbine. This amounts to a 21.3 GJ/h heat load, heating condensate from 46°C to 95°C. This results in a dryer sized to dry 31% of the bark, wood waste and sludge fuel from 50% to 25%, the balance being fired with the as received moisture content. The dried material then rejoins the balance of the fuel and is conveyed to the metering bin and stokers for firing. In this way, the average dryness of the mixture is reduced by about 6% wet basis.

The addition of the bed mixing steam dryer has a number of effects on combustion, temperatures and heat transfer in the boiler. The heat in the hot bed material extracted from the fluid bed furnace results in lower furnace combustion temperatures while firing drier fuel. The lower flue gas temperature, due to removal of heat with the bed material, reduces the heat available for heating air in the tubular air heater and results in a lower stack temperature. Combustion air heating is therefore reduced somewhat, which incrementally reduces boiler efficiency. Compensating this and tending to increase boiler efficiency incrementally is the reduction of the flue gas temperature leaving the tubular air heater. The steam cycle is also affected as the heat recovered from the dryer steam, used to heat returning condensate, reduces the deaerator steam demand and extraction steam flow and increases power generation. Estimates of these effects were prepared using boiler efficiency calculations linked to simplified steam cycle heat balances, and the results are preliminary. Confirmation of the feasibility of the concept requires the participation of the boiler modification supplier and Foster Wheeler, the development of detailed heat balances for each month or season to evaluate the full range of operating conditions and evaluation of the kraft pulp mill water system to optimize the points of heat absorption.

In this preliminary evaluation, the IVO a Bed Mixing dryer would dry 14 200 ODkg/h of wood refuse from 50% to 25% moisture content wet basis, evaporating 9450 kg/h water.

The principal effects of changes to the boiler and steam cycle based on the results of this preliminary analysis are presented in Table 5 - 6.

Table 5-6
Summary of Preliminary Estimated Changes to Combustion Process and Steam Cycle[(a)] Fluidized Bed Boiler Cogeneration Case

		Unit	Base Case	With New Steam Dryer
Wood Fuel Moisture Content:	as received	%	50	50
	as fired	%	50	44.3
Stack temperature		°C	200	182.5
Boiler Efficiency		%	66.5	69.8
Wood Refuse Fuel Used		ODkg/h	40 900	46 300
Power Generation (b)		kW	15 797	25 026
Turbine Heat Rate		GJ/kW	12 368	11 899

Notes:
a - assumes identical actual wet volumetric flow rates entering the boiler generating bank at the temperature.
b - power generation from a hypothetical condensing-type steam turbine generator

Fuel Costs, Power consumption and other Operating Costs

The cost of fuel delivered to the mill is taken to be zero.

The parasitic power consumption of the plant will increase with steam drying because of additional feeders, conveyors and the dryer steam blower recirculating the bed material and dried fuel into the cyclone. The small power change for the induced draft fans has been ignored as the volumes of flue gases are not significantly changed, but the forced draft fan will handle about 8% more volume, consuming an additional 75kW. The allowance for the additional power consumed by the dryer is 300kW, making a total of 375kW for the dryer option.

A nominal allowance of 2% of total installed cost annually has been made in the economic evaluation to provide for additional operating and maintenance labour and maintenance materials, property taxes insurance, administration and overhead associated with the steam dryer.

Investment costs

The capital costs for steam drying have been based on preliminary estimated supply and erect prices developed by IVO, with the balance of the installation being based on factored estimates which are considered appropriate for this preliminary screening type of economic analysis. This includes an allowance for changes to the wood handling system to divert 34% of the wood fuel flow to the Bed Mixing dryer. The preliminary order of magnitude capital cost is estimated at 6.1M$.

The condensing turbine will be larger by about 10MW. Using an estimate of 800$ per MW of capacity, the additional investment will be 8M$. Total investment is therefore assumed to be of the order of 14M$.

Economics and Return on Investment

The results of the estimated changes in fuel and power consumption on the return on investment for flue gas drying options considered is presented in Table 5 - 7.

Table 5-7
Capital Costs, Operating Costs and Return on Investment Fluidized Bed Boiler Cogeneration Case

		Unit	Base Case	With New Steam Dryer and larger TG
Incremental Wood Refuse Fuel Fired		ODkg/h	Base	5367
Power Generated	Gross Additional	kW	Base	9229
	Net Additional	kW	Base	8854
Capital Costs, Incremental, Steam Dryer and larger condensing section in the steam turbine generator		M$	Base	14
Operating Costs [(a)]	Wood Refuse 0$/ODT	$/a	Base	0
	Incremental Power 35$/MWh	$/a	Base	2 603 000
	Less: Other Operating Expenses 2% of TIC	$/a	Base	320 000
	Total Operating Savings	$/a	Base	2 283 000
Payback, Gross, on Incremental Capital Cost		a		6.3

Notes: a - Based on 8400h/a

A

GLOSSARY OF TERMS, ABBREVIATIONS AND UNITS

a	annum, year
ABB	Asea Brown Boveri of Winterthur, Switzerland
ACFM	actual cubic feet per minute
AD	air dry, which when referring to pulp contains 10% moisture by definition, but when referring to paper contains the % moisture of the product (typically 7%), both on a wet basis.
ADt	air dry metric tonnes (2205 lb)
ADT	air dry ton (2000 lb)
ADTP	air dry ton pulp
ADt/a	air dry metric tonnes per annum
ADt/d	air dry metric tonnes per day
Atm.	atmospheric
^{Am}	volume in cubic meters at the actual wet conditions of the gas
ADm^3	dry volume in cubic meters at the actual conditions of the gas
BC	Province of British Columbia, Canada
BD	bone dry, equivalent to oven dry, containing no free moisture
BDt	bone dry metric tonne (same as oven dry)
BDt/d	bone dry metric tonne per day
BLS	black liquor solids, bone or oven dry
BOD	5 day biochemical oxygen demand
Btu	British thermal unit
CH_4	methane
°C	degrees Celsius
d	day
D	dry gas conditions
DS	dry solids
d/a	days per annum
ft^3	cubic feet
g	gram
G	giga, 10^9
GJ	gigajoule
g/L	grams per liter
h	hour
HAP	hazardous air pollutants, as identified on a list in U.S. jurisdictions
HNO_3	nitric acid
HP	high pressure, usually referring to steam
hp	horsepower

ID	induced draft, as in fan
IVO	Imatran Voima Oy (see pg 4 - 20)
k	kilo, 10^3
kg	kilogram
kg/ADt	kilograms per air dry metric tonne
kJ	kilojoule
km	kilometer
kPa	kilopascal
kPag	kilopascal gauge
kW	kilowatt
kWh	kilowatt hour
L	liter
LA	State of Louisiana
lb	pound
LP	low pressure, usually referring to steam
LRF	lumber recovery factor, fraction of lumber per log
L/s	liter per second
MBtu	million British thermal units
MCR	maximum continuous rating of a boiler. 100 % of nameplate rating for a specified fuel
m	meter
M	mega, 10^6
ME	State of Maine
MJ	megajoule
MP	medium pressure, usually referring to steam
MPa	megapascal
MW	megawatt
mg	milligram
min.	minute
m^2	square meter
m^3	cubic meter
m^3/ADt	cubic meter per air dry metric tonne
m^3/d	cubic meter per day
m^3/h	cubic meter per hour
N	normal conditions, an SI standard of 0°C and 101.325 kPa
NA	not applicable

NCASI	National Council of the Paper Industry for Air and Stream Improvement Inc.
NCG	non-condensible gas
ng	nanogram, 10^{-9} g
NH	State of New Hampshire
NO	nitric oxide
NO_x	nitrogen oxides
N_2O	nitrous oxide
OD	oven dry, same as Bone Dry (BD)
OR	State of Oregon
O_2	oxygen
O_3	ozone
Pa	Pascal
PB	power boiler
PCB	polychlorinated biphenyls
PCDD	polychlorinated dibenzo-p-dioxins
PCDF	polychlorinated dibenzofurans
PCDD/F	polychlorinated dibenzo-p-dioxins and furans
pH	relative acidity or alkalinity
PM	particulate matter or total suspended particulate
ppb	parts per billion, 10^9
ppm	parts per million, 10^6
ppm_{dv}	parts per million dry volume basis
psig	pounds per square inch gauge
s	second
S	sulphur, or, standard gas conditions of temperature and pressure as specified, e.g.: 20°C and 101.325 kPa, depending on the context
SCFM	standard cubic feet per minute
SCR	selective catalytic reduction
SD	Standard (refer abbreviation S), dry
SO_2	sulphur dioxide
SO_3	sulphur trioxide
SO_x	sulphur oxides
t	metric tonne (2205 lb)
T	short ton (2000 lb)
tADP	tonne air dried pulp
TADP	ton air dried pulp

TAPPI	Technical Association of the U.S. Pulp and Paper Industry
TCDD	tetrachlorodibenzo-p-dioxin
TCDF	tetrachlorodibenzofuran
TGNMO	total gaseous non-methane organic compound, or VOC
TIC	total installed cost
tBLS	tonne black liquor solids
TBLS	ton black liquor solids
t/ADt	metric tonnes per air dry metric tonne
t/a	metric tonnes per annum (year)
t/d	metric tonnes per day
t/h	metric tonnes per hour
USgal	U.S. gallons
U.S.	United States of America
USEPA	United States Environmental Protection Agency
VOC	volatile organic compound
W	watt
wet kg	weight of material with its moisture
WA	State of Washington
WC	water column
%	percent
% O_2	reference oxygen conditions in percent by volume dry basis
Δp	differential pressure
Σ	sum of
µg	microgram, 10^{-6}g
$	U.S. Dollars
$M/a	millions of U.S. dollars per year
$Cdn	Canadian dollars
η	efficiency

B

REFERENCES

Adams, T.N., "Particle Burnout in Hog Fuel Boiler Furnace Environments", Tappi, Vol. 60, No. 2, February, 1977.

Appel Consultants, Inc. *Biomass Energy Fundamentals.* Research Project 3295-01. Prepared for Electric Power Research Institute, Palo Alto, CA, 1993.

Araki, D. "Recovery of Pulp Chips from Non-Traditional Sources". *Proceedings of Residual Wood Residue to Revenue Conference.* Sponsored by Logging and Sawmilling Journal, Richmond, B.C., Nov. 7 and 8, 1995.

Babcock & Wilcox, *Steam, its Generation and Use* 1992 40th Edition, p28-2.

Barsin, J.A., Pottera, J., Stewart, G., *Conversion of a recovery boiler to bark burning*, Technical Association of the Pulp and Paper Industry (TAPPI) Journal, March 1988, p107.

Bechtel Corporation. *Lignite Upgrading Feasibility Study*. Prepared for North Dakota Industrial Commission, Bismark, ND., 1993.

Bergeron, M. "Peat". *Canadian Minerals Yearbook*, 1994. Ottawa, Natural Resources Canada, Mining Sector, 1995.

Black & Veatch, *Wastewater Biosolids and Water Residuals: Reference Manual on Conditioning, Thickening, Dewatering and Drying*, September 1995.

Blackwell, B. R., McCallum, C. et al, *Preparation of Wood for Combustion*, Canadian Electrical Association, April 1984.

Bole, W.P. "Peat- 1993", *Minerals Yearbook, 1993,* U.S. Department of the Interior, Bureau of Mines, 1994.

British Columbia. Ministry of Environment. *Wood Residue Burner and Incinerator Regulation.* B.C. Reg. 519/95. December 7, 1995.

Brown, Richard of EPRI, Palo Alto, CA, USA. Personal communication mid- July 1996

Bruce, D. M, Persson, B. S., Grabovac, J. Nygaard, J. *Sludge Disposal - Current Practices and Issues*, Pacific Paper Expo, 1991.

Burns and Roe, Inc. *Evaluation of Peat as a Utility Boiler Fuel.* Research Project 1838-1. Prepared for National Rural Electric Cooperative Association (Wash., D.C.), North Carolina Electric Membership Corporation (Raleigh, N.C.), and Electric Power Research Institute (Palo Alto, CA), 1983.

Caule, R.P., Clayton, D.W. and Simonsen, I. *Energy-Efficient Process for the Pulp and Paper Industry: Analysis of Selected Technologies*. CANMET Project No. EA 97209-12. Department of Natural Resources Canada, Ottawa, 1995.

Combustion Engineering, *Combustion Fossil Power*, published by Combustion Engineering Inc., division of Asea Brown Boveri, 1991.

Fagernäs. L, Sipilä, K. *Emissions of Biomass Drying*, to be published in the Proceedings for the conference on Developments in Thermochemical Biomass Conversion, Banff, AB, Canada, 20 - 24 May 1996.

Forrest, R.D. "The Recycling Cycle", *Canadian Papermaker*, January 1995. Maclean Hunter Publishing Ltd., Toronto.

H. A. Simons and B. H. Levelton, *Data Book on Unit Processes for Fuel Preparation and Handling* (Volume III, ENFOR C-258, 1983). for Environment Canada under the ENFOR program, December 1983.

H.A. Simons Ltd. *Elko Cogeneration Project Pre-Feasibility Study*. Prepared for Alberta Natural Gas Co. Ltd. July 1994.

H.A. Simons Ltee. *Biomass Prospects for Future Electricity Generation Plants: A Canadian Perspective*. Prepared for the Canadian Electrical Association. CEA Report No. 9230 G969, 1994.

Haynes, R.W., Adams, D.M., and Mills, J.R. *The 1993 RPA Timber Assessment Update*. USDA. Forest Service. Rocky Mountain Forest and Range Experiment Station. General Technical Report RM-GTR-259. 1995.

Hulkkonen, S., Heinonen, J., Tiihonen, J., Imppola, R., *Drying of Wood Biomass at High Pressure Steam Atmosphere; Experimental Research and Application*, Drying Technology, 12(4), p869 - 887, 1994

Hulkkonen, S., IVO Finland liaison at EPRI. Personnal communication, July 1996

Hupa, M., *Deposit Formation in Boilers Fired with Bark Alone or in Combination with Other Fuels*, Papper och Trä, No 8, 1977.

International Cane Energy News, July 1994.

Jain, Ashok, Personal communication, 11 April 1996. Mr Jain is the chief Air Emission specialist with the NCASI, in Gainsville, FL, tel: 904-377-4708.

Jensen, Arne S., NIRO A/S, Copenhagen, Denmark, *Industrial Steam Fluid Bed Drying Under Pressure*, The 9th International Drying Symposium, Brisbane, Australia, August 1994.

Jensen, Arne S., NIRO A/S, Copenhagen, Denmark, *Pressurised Steam Drying of Sludge, Bark and Wood Chips*, Pulp and Paper Canada, 97:7 (1996), July 1996.

Johnson, L.R. and Folk, R.F. *Summary of Forest Residue Recovery Options: Cost and Production Rates for Harvesting and Processing Forest Residues*. Forest Products Department, University of Idaho, Moscow, Idaho. Submitted to Martin Marietta Energy Systems. Subcontract Number SSS700-28. July 24, 1995.

Johnson, R.C., *Some aspects of Wood Waste Preparation for Use as a Fuel*, TAPPI, Vol 58, No. 7, July 1975, p102.

Kinoshita, C.M. " Flue Gas Drying of Bagasse", *Applied Engineering in Agriculture*, Vol.7, no. 6, pp. 729-734, 1991.

Kraft, David L. and Orender, Hayes C. *Considerations Using Sludge As A Fuel*, Tappi 1991 Engineering Conference.

Levelton, B.H. & Associates Ltd.;"An evaluation of wood waste enery conversion systems" Report for the BC Wood Waste Energy Co-Ordinating Committee, BC Energy Commission, COFI, and EMR Canada, March, 1978.

B. H. Levelton, *Update of Data Book on Unit Processes for Fuel Preparation and Handling* (final draft) (originally Volume III, ENFOR C-258, 1983, by H. A. Simons and B. H. Levelton) for Energy Technology Branch - CANMET, Natural Resources Canada, February 1993.

Linderoth, C. E., *Why dry hog fuel ?* Pulp and Paper Canada, Vol 87:6 (1986), p103

Louhimo, Jukka T., and Mullen, John F. *Sludge burning in Fluid Bed Boilers*. Tappi 1990 Engineering Conference.

Luthe, C., Karidio, I., Uloth, V. *Controlling Dioxin Emissions in Coastal Boilers: a Status Report* Pulp and Paper Canada, Vol 97:9 (1996), p76

Mackie, K. L. *The nature and control of solid, liquid and gaseous emission from thermochemical processing of biomass,* New Zealand Forest Research Institute, Rotorua, New Zealand. Report No. ES 94/2 of the Task X, Activity & - Environmental Systems, International Energy Agency, January, 1995

McCallum, C. Blackwell, B.R., Torsein, L., *Cost Benefit Analysis of Systems Using Flue Gas or Steam for Drying of Wood Waste Feedstocks*, Canadian Forestry Service, Environment Canada, October, 1981

McDermott, R. J., Morris, K. W., Sanderson, J. G., *a Better Boiler for Wet Hog Fuel*, 66th Annual Meeting of the CPPA, Montreal, January 1980, .

Mensch, R. "Classification of Log Yard Debris". *Proceedings of Residual Wood Residue to Revenue Conference.* Sponsored by Logging and Sawmilling Journal, Richmond, B.C., Nov. 7 and 8, 1995.

Mikkola, Jussi, of Ahlstrom Machinery Inc. Camas, WA, USA. Personal communication 30 April 1996

Morris, G. "The Future of the Biomass Power Industry in California", *Bio Bulletin*, Vol. II, Issue

National BioEnergy Industries Association, *Biologue and the Regional Biomass Energy Program Reports*, Volume 13, Number 4 - 4th quarter 1995. IV, April 1995.

NBIA, Biologue, 4th Quarter, of the National Bio Energy Industries Association, 1995, p. 17.

NCASI (National Council of the Paper Industry for Air and Stream Improvement, Inc.).. Technical Bulletin No. 587*, Response Of Selected Pulp And Paper Industry Solid Wastes To The RCRA Toxicity Characteristic Leaching Procedure*, May 1990.

NCASI (National Council of the Paper Industry for Air and Stream Improvement, Inc.). Technical Bulletin No. 613*, Characterization of Wastes and Emissions from Mills using Recycled Paper*, September 1991.

NCASI (National Council of the Paper Industry for Air and Stream Improvement, Inc.). Technical Bulletin No. 615, *Current status of Nonrecyclable Paper Burning in the Forest Products Industry*, Sept. 1991.

NCASI (National Council of the Paper Industry for Air and Stream Improvement, Inc.). Technical Bulletin No. 641, *Solid Waste Management and Disposal Practices in the U.S. Paper Industry*, September, 1992.

NCASI (National Council of the Paper Industry for Air and Stream Improvement, Inc.). Technical Bulletin No.657, *A Study of Volatile Organic Compound and Condensibel Particulate Matter measurement methods used on Furnish Dryers in the Oriented Strandboard Industry*, January, 1994.

NCASI (National Council of the Paper Industry for Air and Stream Improvement, Inc.). Technical Bulletin No. 693, *Particleboard and Medium Density Fibreboard Air Emission Databases,* April, 1995.

NCASI (National Council of the Paper Industry for Air and Stream Improvement, Inc.). Technical Bulletin No. 694, *Strandboard and Plywood Air Emission Databases,* April, 1995.

NCASI (National Council of the Paper Industry for Air and Stream Improvement, Inc.). Technical Bulletin No. 695, *An Air Emission Database for Wood Product Plant Combustion Units,* April, 1995.

Nielson, R.W., Dobie, J. And Wright, D.M. *Conversion Factors for the Forest Products Industry in Western Canada*. Special Publication No. SP-24R. Forintek Canada Corp., Vancouver, B.C., 1985.

Nowacki, Perry, Ed. Lignite Technology. Noyes Data Corporation, Park Ridge, N.J., 1980.

Offen, George, Electric Power Research Institute, Personal communication, May 1996.

Peetso, V. *Recovering Usable Fibre*. Proceedings of Residual Wood Residue to Revenue Conference. Sponsored by Logging and Sawmilling Journal, Richmond, B.C., Nov. 7 and 8, 1995.

Papermaker, *Burning for Dollars*, April 1993, p42.

Pulp and Paper, *Cascades Mill Reudces Energy Cost by Converting to Wood-Fired Boiler* September, 1993.

Robinson, L. *Suspension-fired Biomass Boilers* TAPPI Journal, August 1986.

Sanderson, J.G., Hog Fuel Drying Using Boiler Stack Gases at Canadian White Pine", Western Branch Meeting, Canadian Pulp and Paper Association, 1979.

Shapiro, L. and Lomas, B. “Coal”, *Canadian Minerals Yearbook, 1994.* Ottawa, Natural Resources Canada, Minerals and Metals Sector, Coal and Ferrous Division, 1995.

Smith, G.G. *Coal Resources of Canada*. Geological Survey of Canada, Paper 89-4. 1989.

Spurrell, R.M., Thorn, P.A.; "Factors Affecting Combustion Efficiency in Wood Fired Boilers", Engineering Conference, 1986.

Spurrell, R.M., Shenk, R.C.; "Evaluating The Performance of Wood-Fired Spreader Stoker Boilers", Engineering Conference, 1984.

Tarnocai, C. *Peat Resources of Canada*. Agriculture Canada, Research Branch, Land Resource Research Institute, 1984.

Timmenga, Hubert J. *Compost and Compost Quality*, Workshop Presentation at the Association of Professional Engineers of B.C. at Kelowna, October, 1991.

U.S. Department of Agriculture. Forest Service. *North Central Forest Experimental Station. Forest Statistics of the United States, 1992* (metric units). General Technical Report #NC-168.

U.S. Department of Energy. Energy Information Administration. *Coal Data: A Reference*. DOE/EIA-0064(93). February 1995.

U.S. Department of Energy. Energy Information Administration. *U.S. Coal Reserves: An Update by Heat and Sulfur Content*. DOE/EIA-0529(92). February 1993.

U.S. Department of Energy. Energy Information Administration. *Coal Industry Annual 1994*. DOE/EIA-0584(94). 1994.

USDA, National Agricultural Statistics Service, 1996.

Välttlä, O., Järvinen, R., Rainio, K., Talka, E., Isomöttönen, K., Alaniemi, M-J., *Combustion of Kraft Biosludge*, TAPPI International Envioonmental Conference, 1994, p49

Warren, Sita. H.A. Simons Ltd. *Hog Fuel Characteristics*. Prepared for Harmac Pacific Ltd., Nanaimo, B.C., February 1995.

Westerberg, L., *Operation of a Flakt Drying System for Bark and Peat in an Existing Linerboard Mill*, Fifth International Forest Products Research Society, International Wood Energy Forum '81, New Orleans, 1981.

Wood Resources International Ltd. *Wood Fibre Northwest, Market Report, December 1995.* Bothell, Wa.